Cosmology and the origin of structure

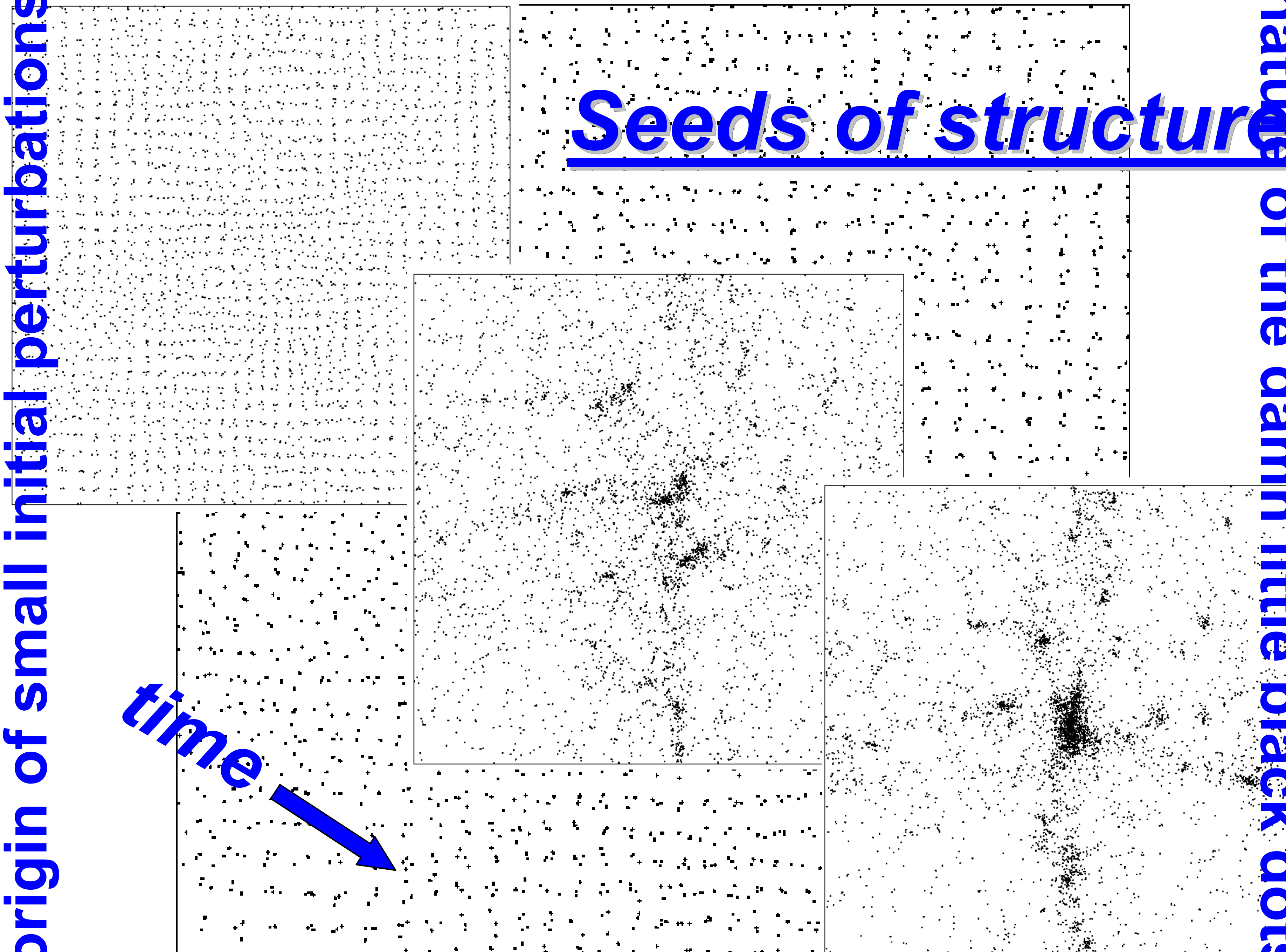
Rocky I:	The universe observed
Rocky II:	The growth of cosmological structure
Rocky III:	Inflation and the origin of perturbations
Rocky IV:	Dark matter and dark energy

Academic Training Lectures

Rocky Kolb

Fermilab, University of Chicago, & CERN

Seeds of structure

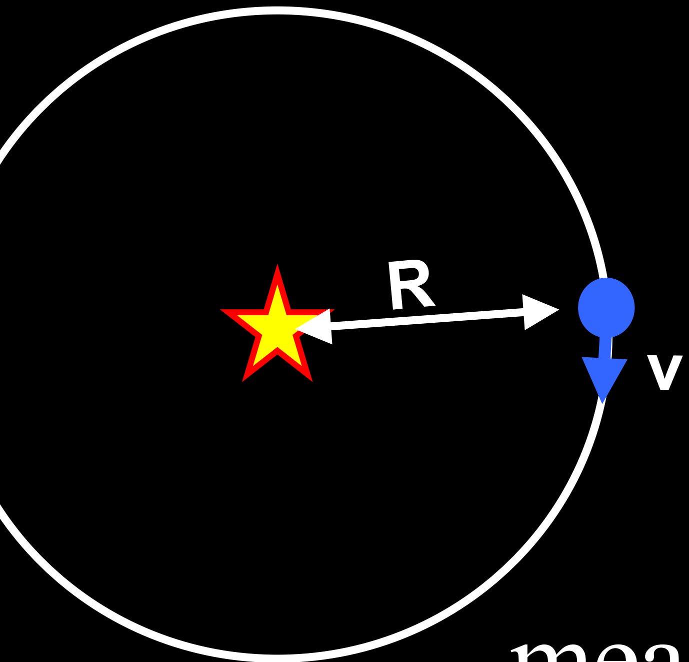


origin of small initial perturbations

nature of the damn little black dots

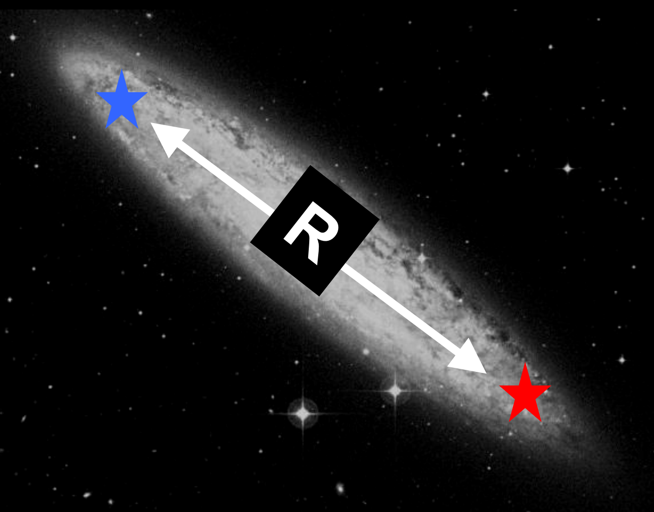
Missing Pieces

Dark Matter



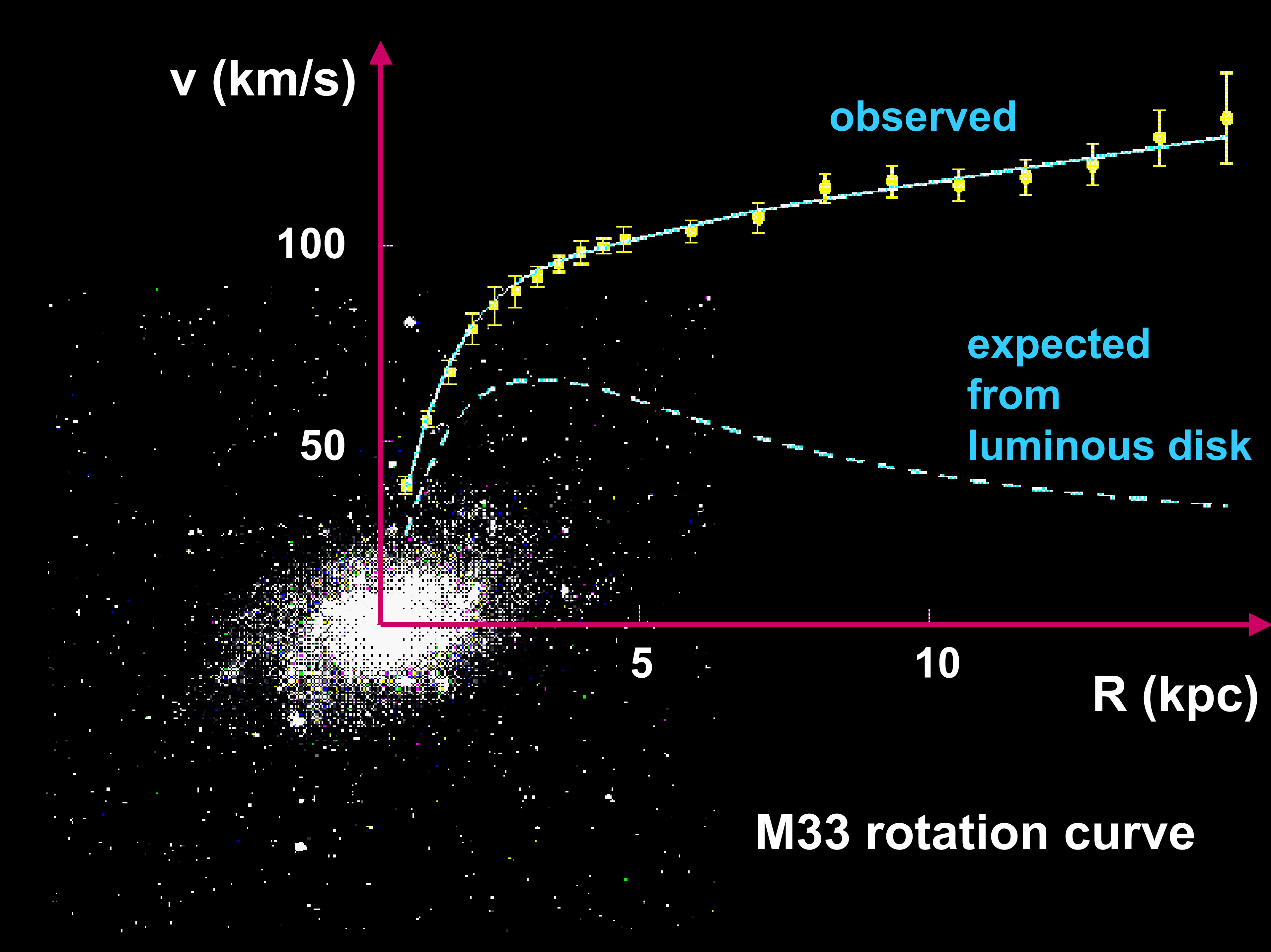
$$\frac{v^2}{R} = \frac{GM_\odot}{R^2}$$

measure v and R $\Longrightarrow$ $M_\odot$



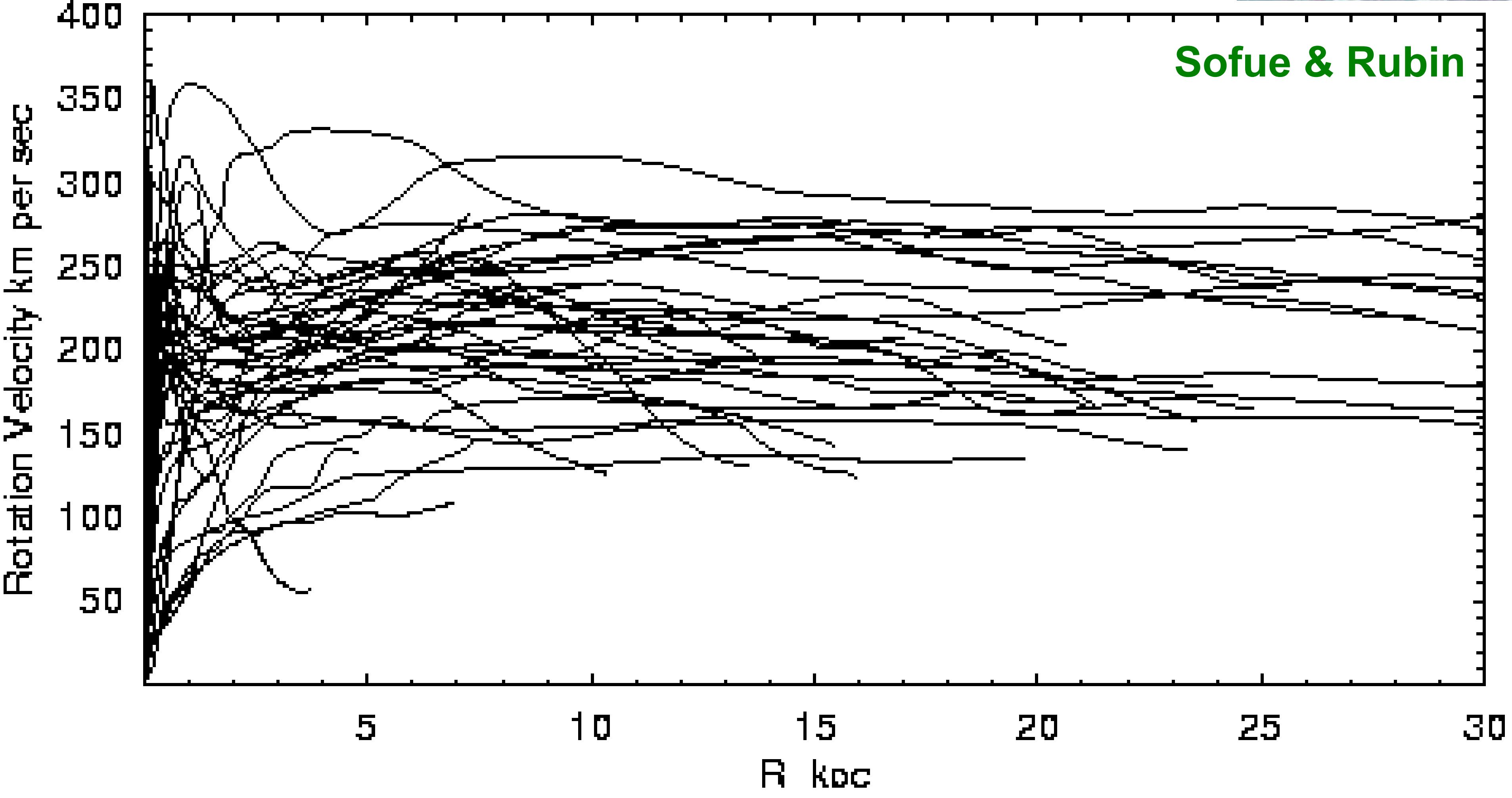
$$\frac{v^2}{R} = \frac{GM_{\mathrm{GALAXY}}}{R^2}$$

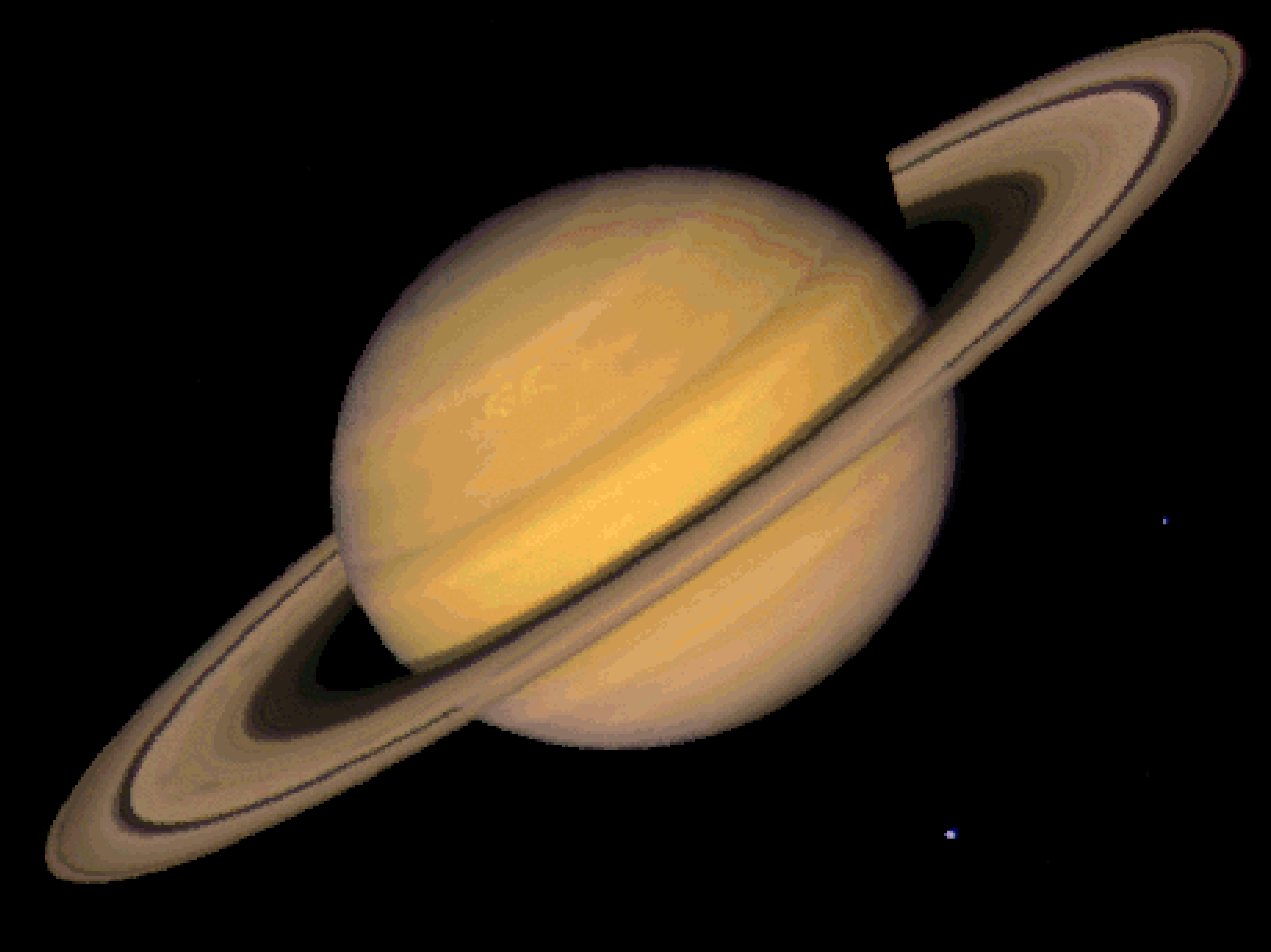
measure v and R $\Longrightarrow$ M_{GALAXY}

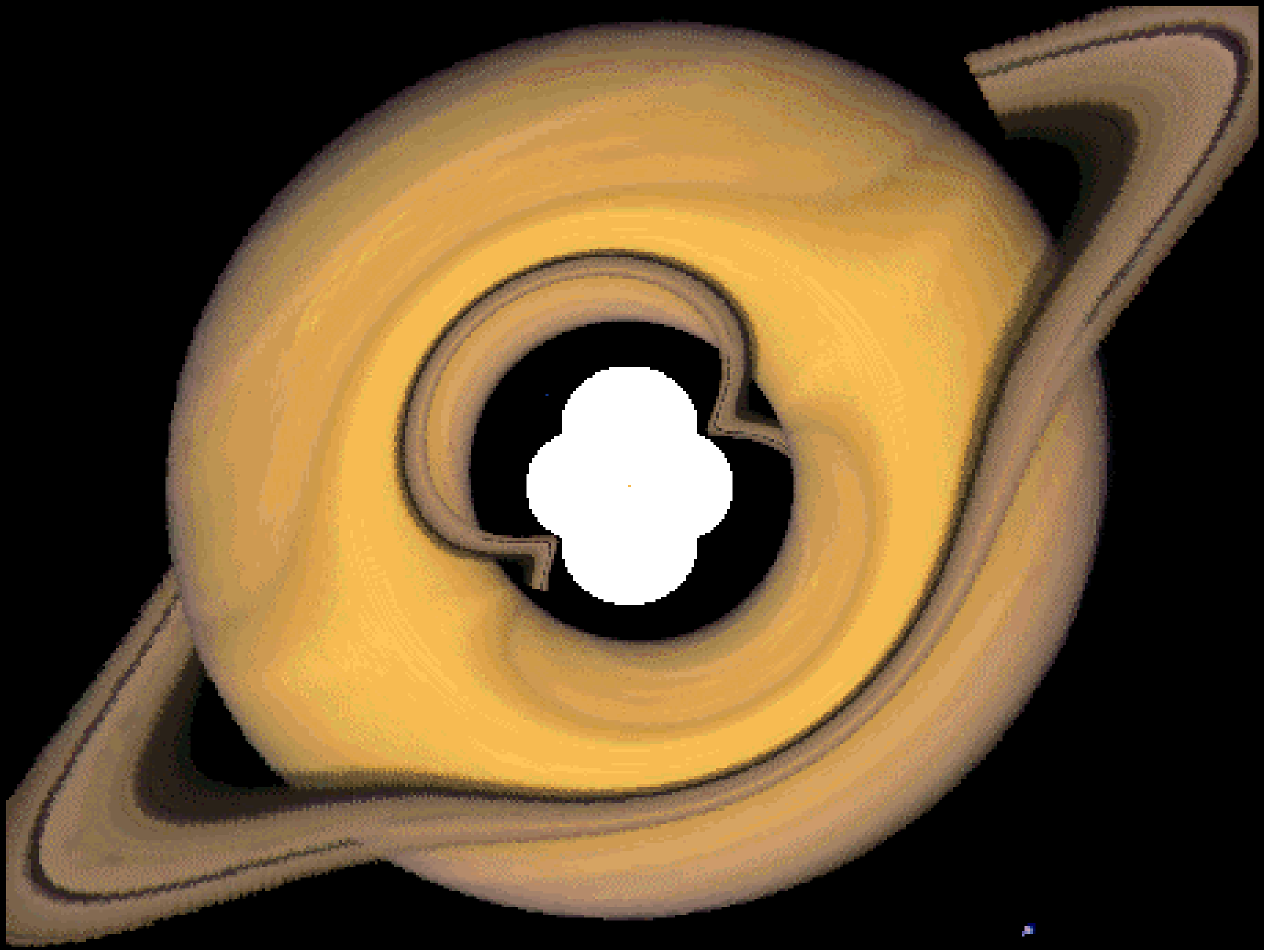

v (km/s)
observed
100
expected
from
luminous disk
50
5
10
R (kpc)
M33 rotation curve

Rotation curves

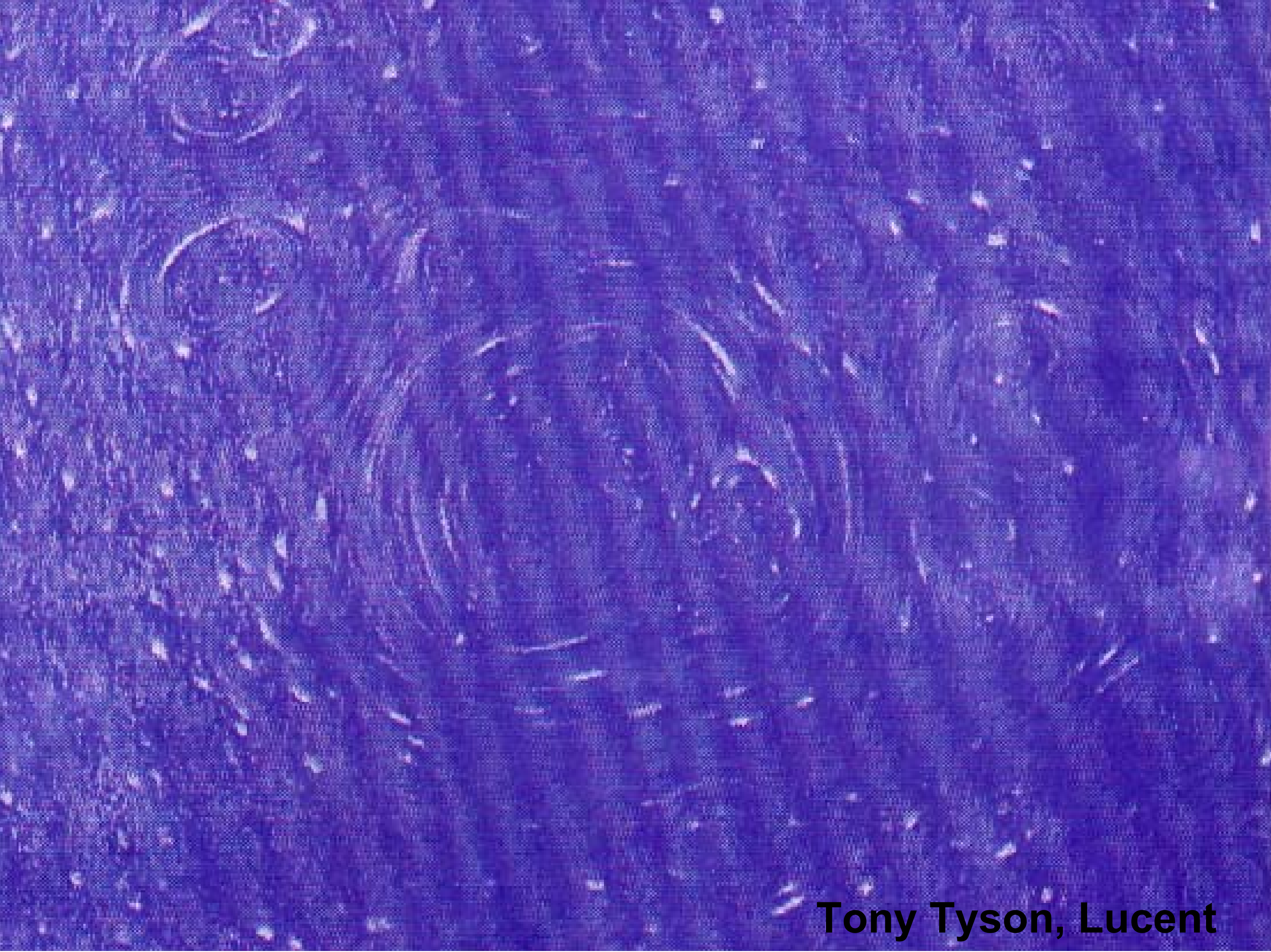
CO – central regions
Optical – disks
HI – outer disk & halo



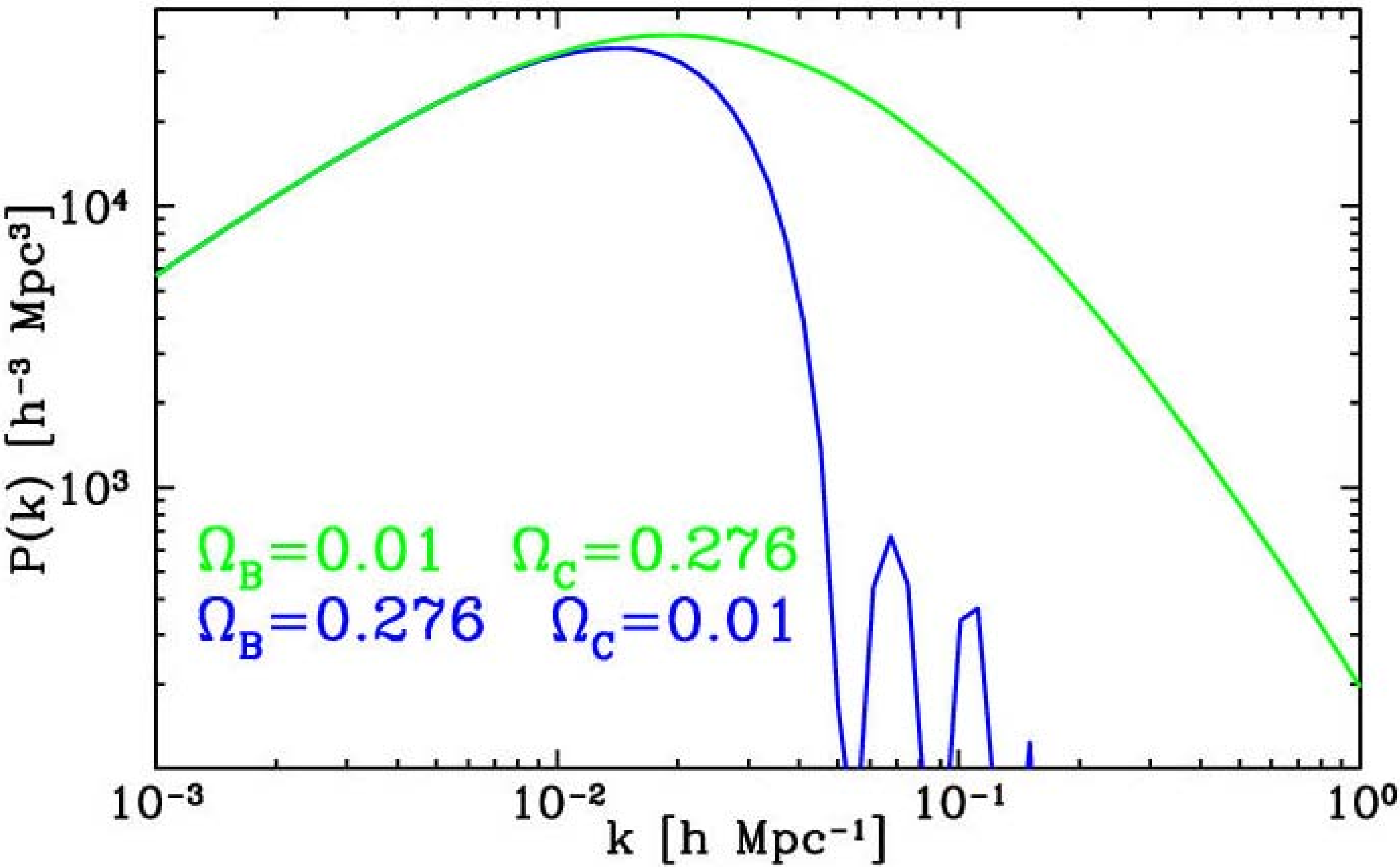




Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2


Tony Tyson, Lucent

The evolved spectrum



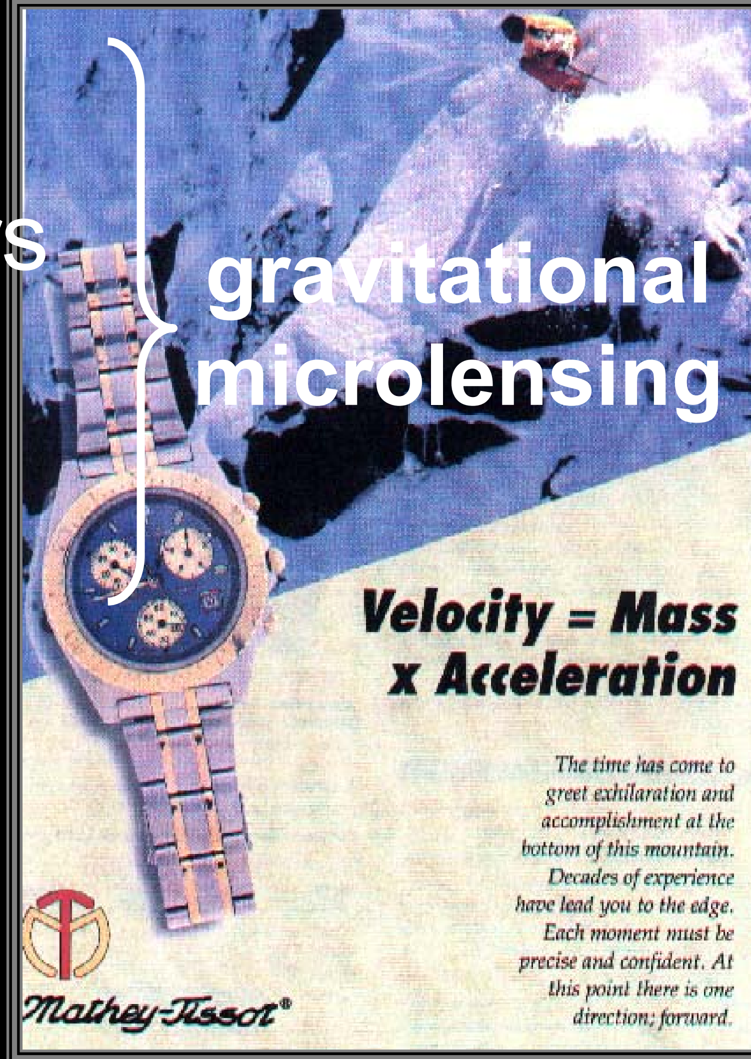
Most of the universe is dark!

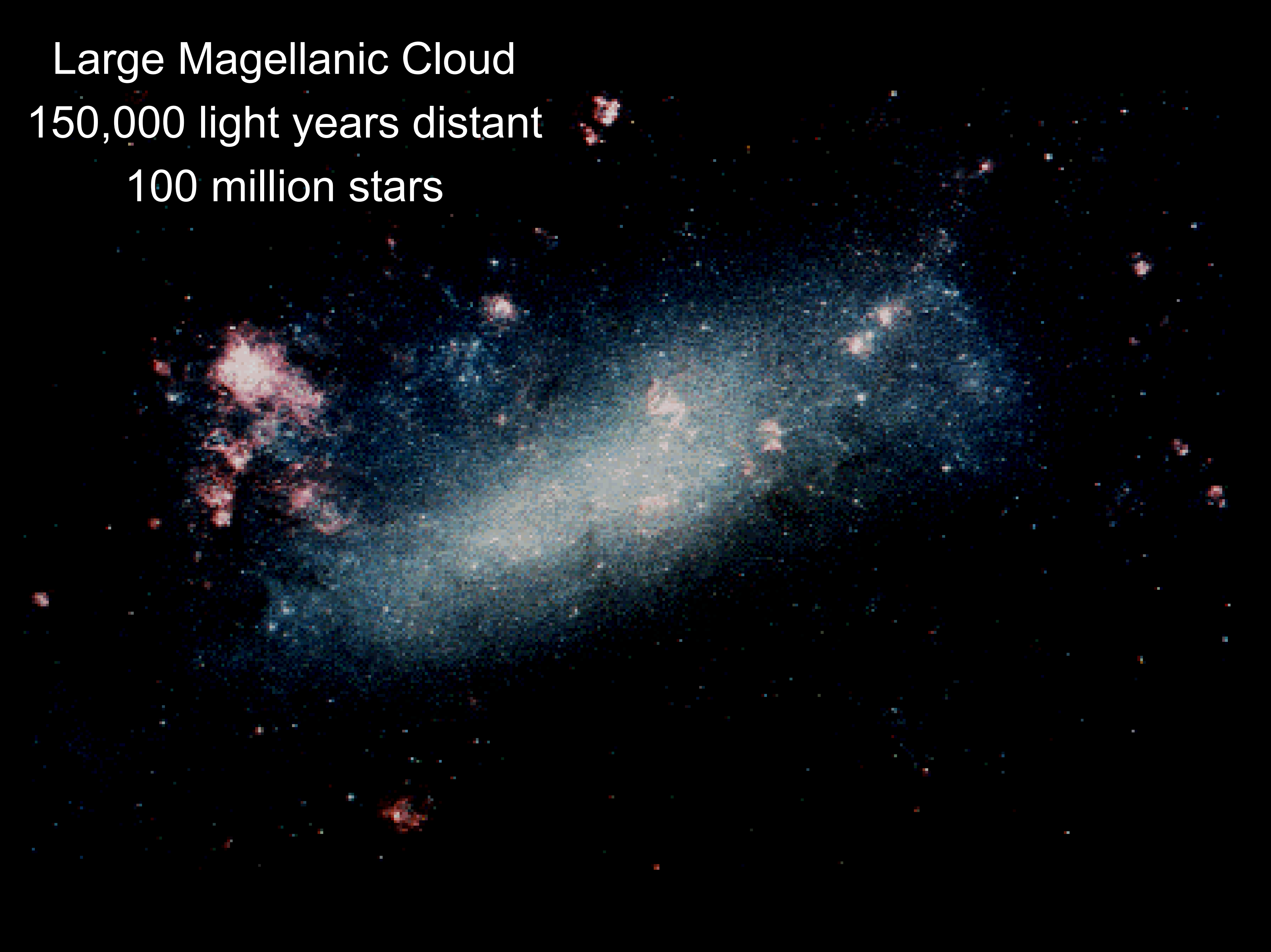
- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars

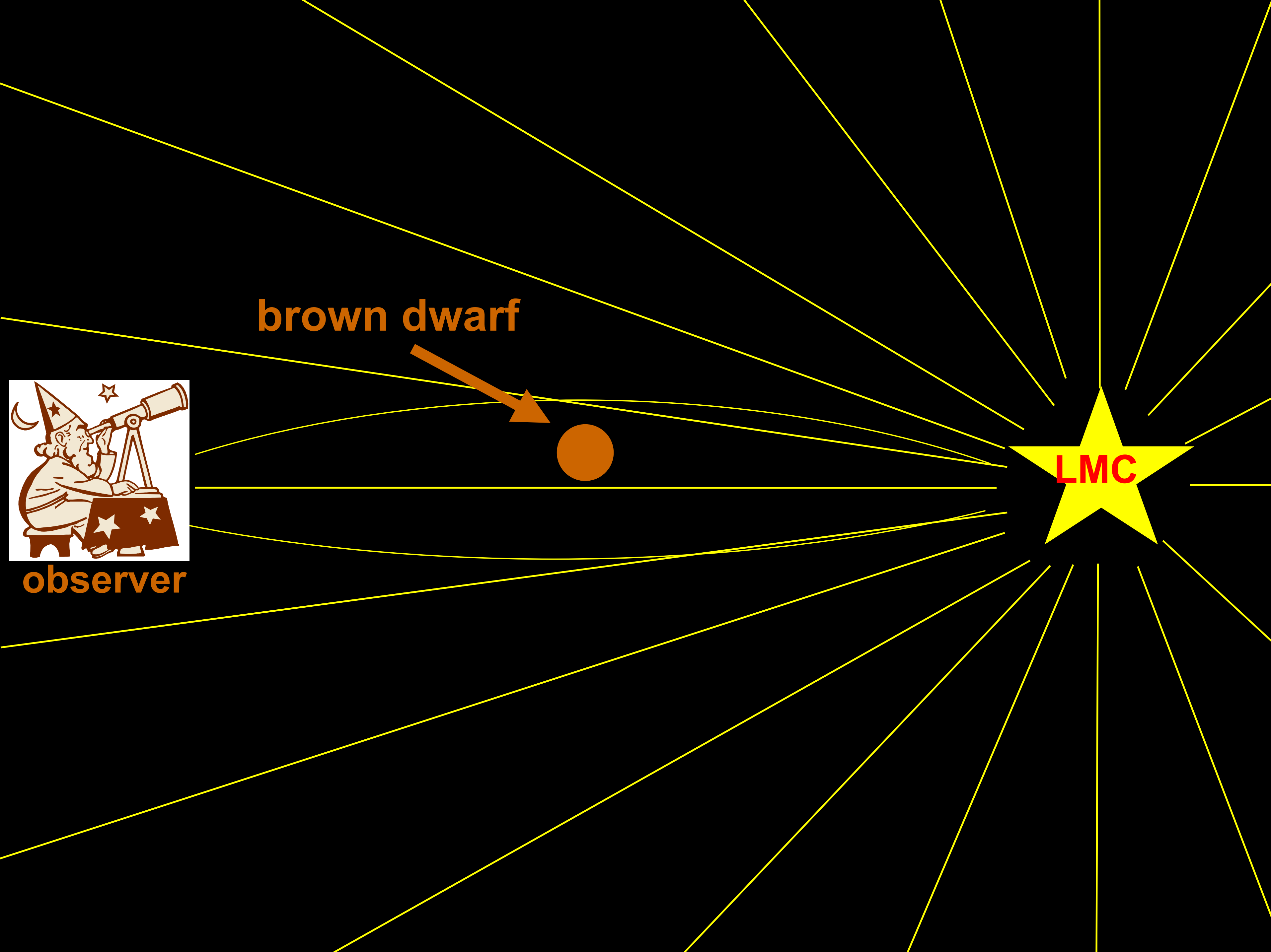
  brown red white

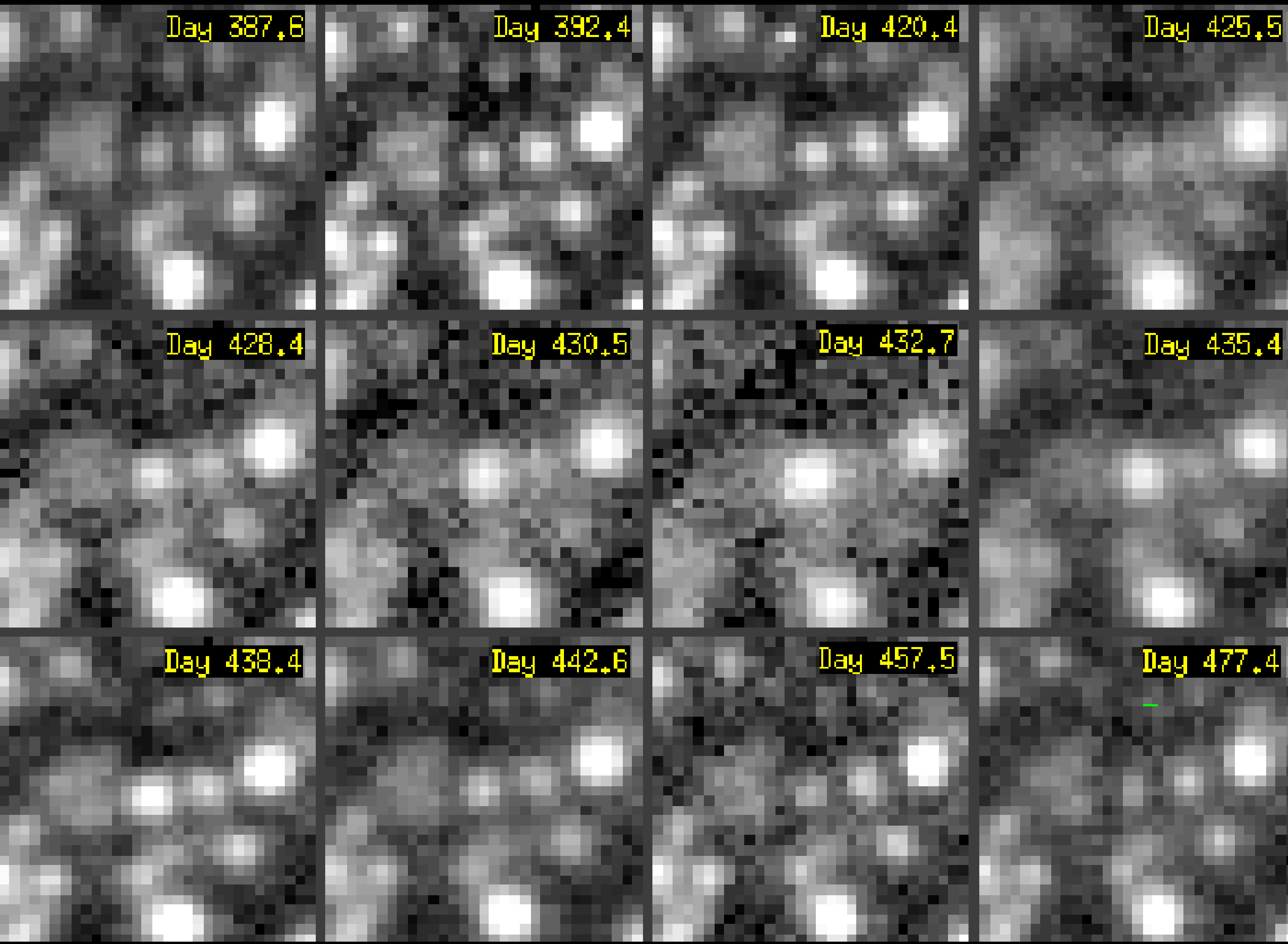
- Black holes

gravitational microlensing

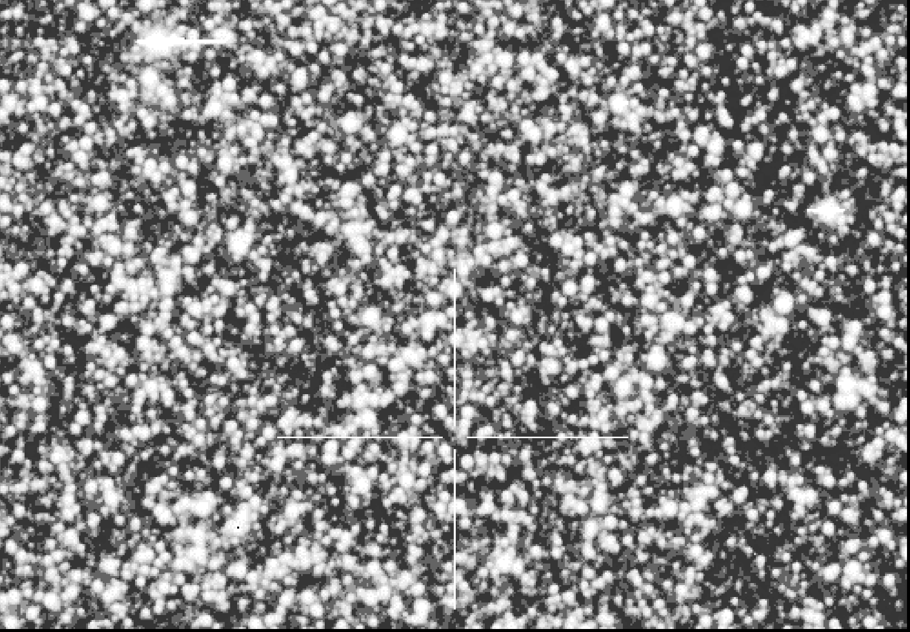


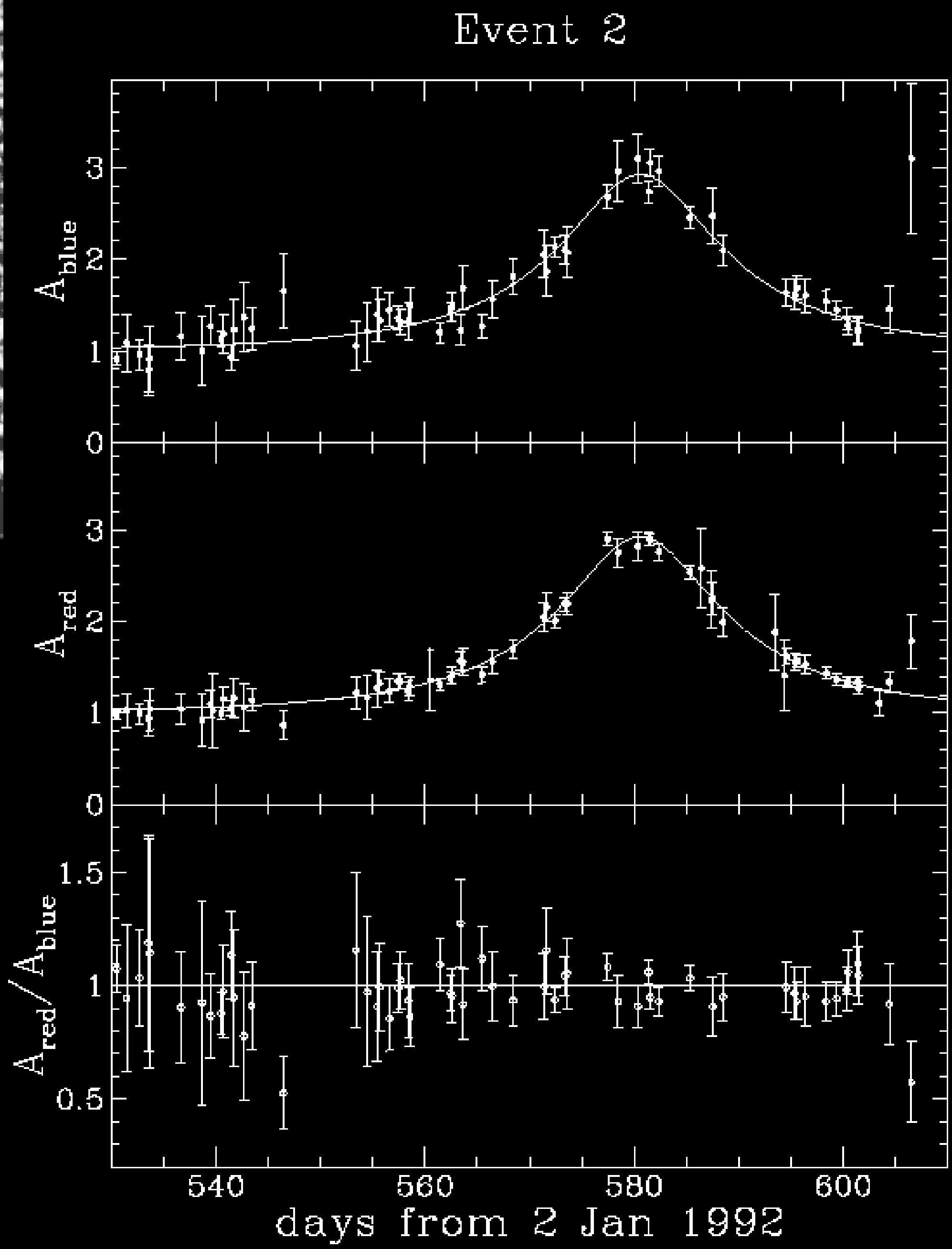

Large Magellanic Cloud
150,000 light years distant
100 million stars


brown dwarf
observer
LMC



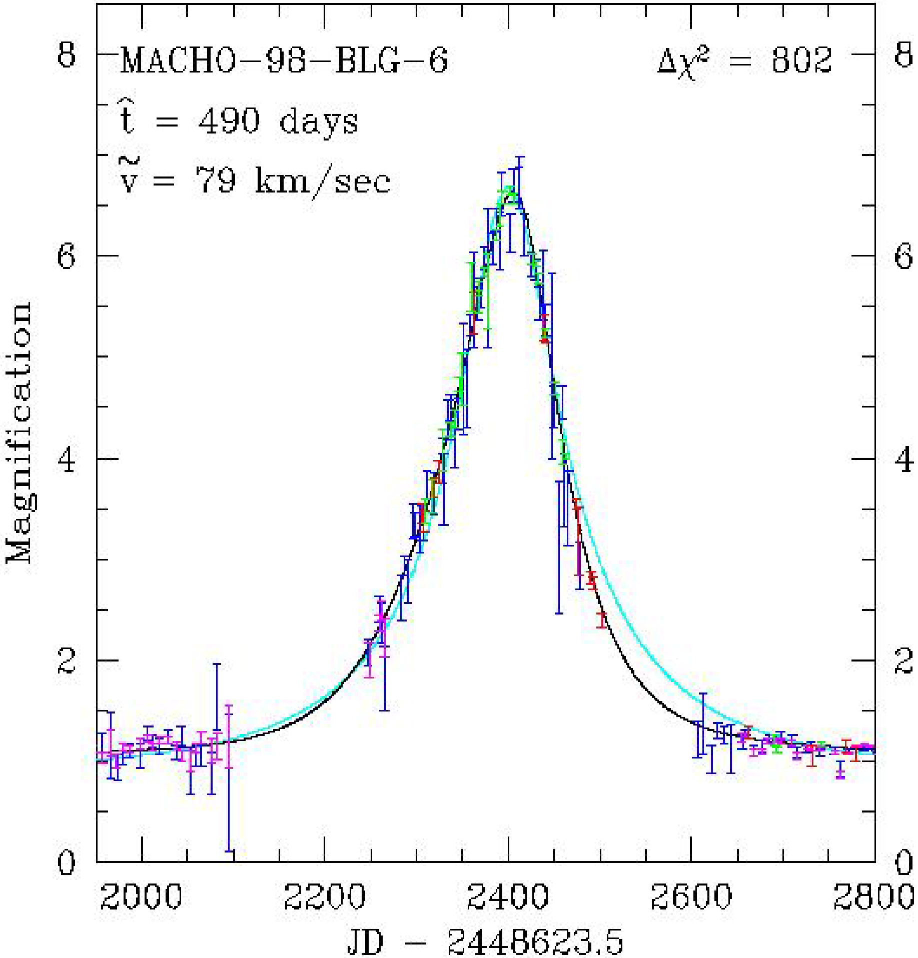
Day 387.6
Day 392.4
Day 420.4
Day 425.5
Day 428.4
Day 430.5
Day 432.7
Day 435.4
Day 438.4
Day 442.6
Day 457.5
Day 477.4

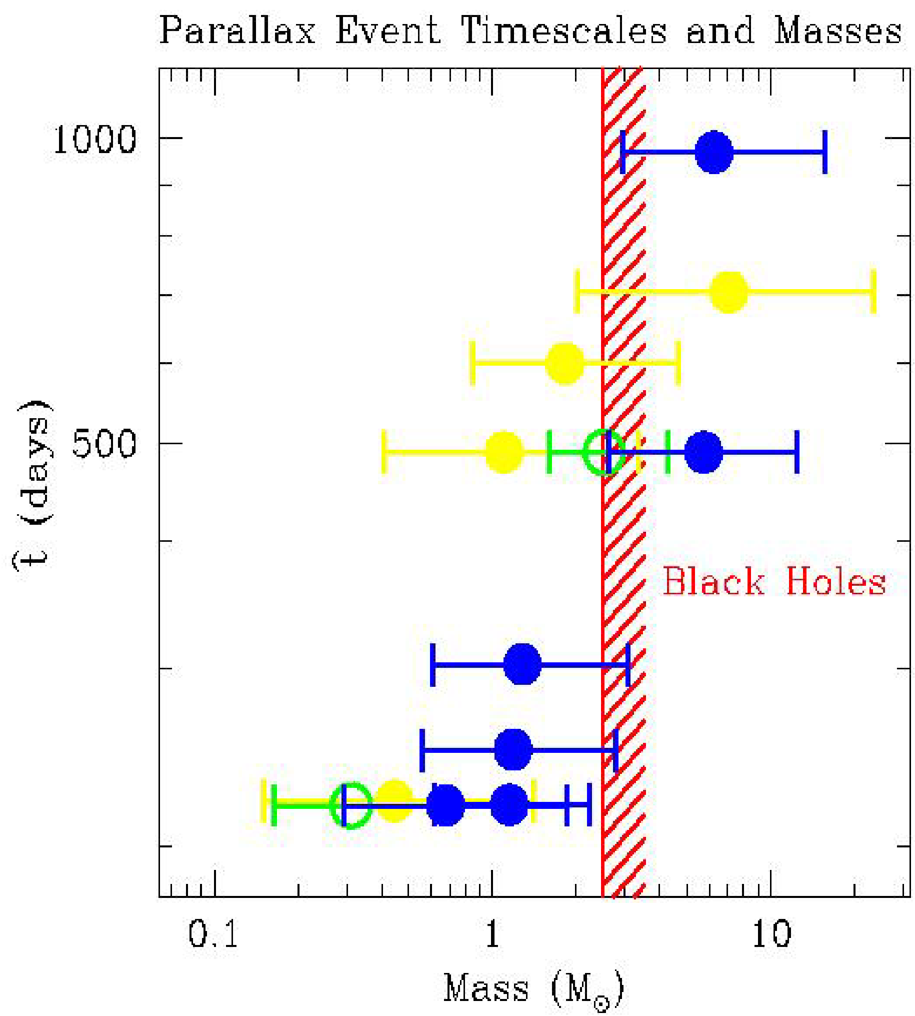




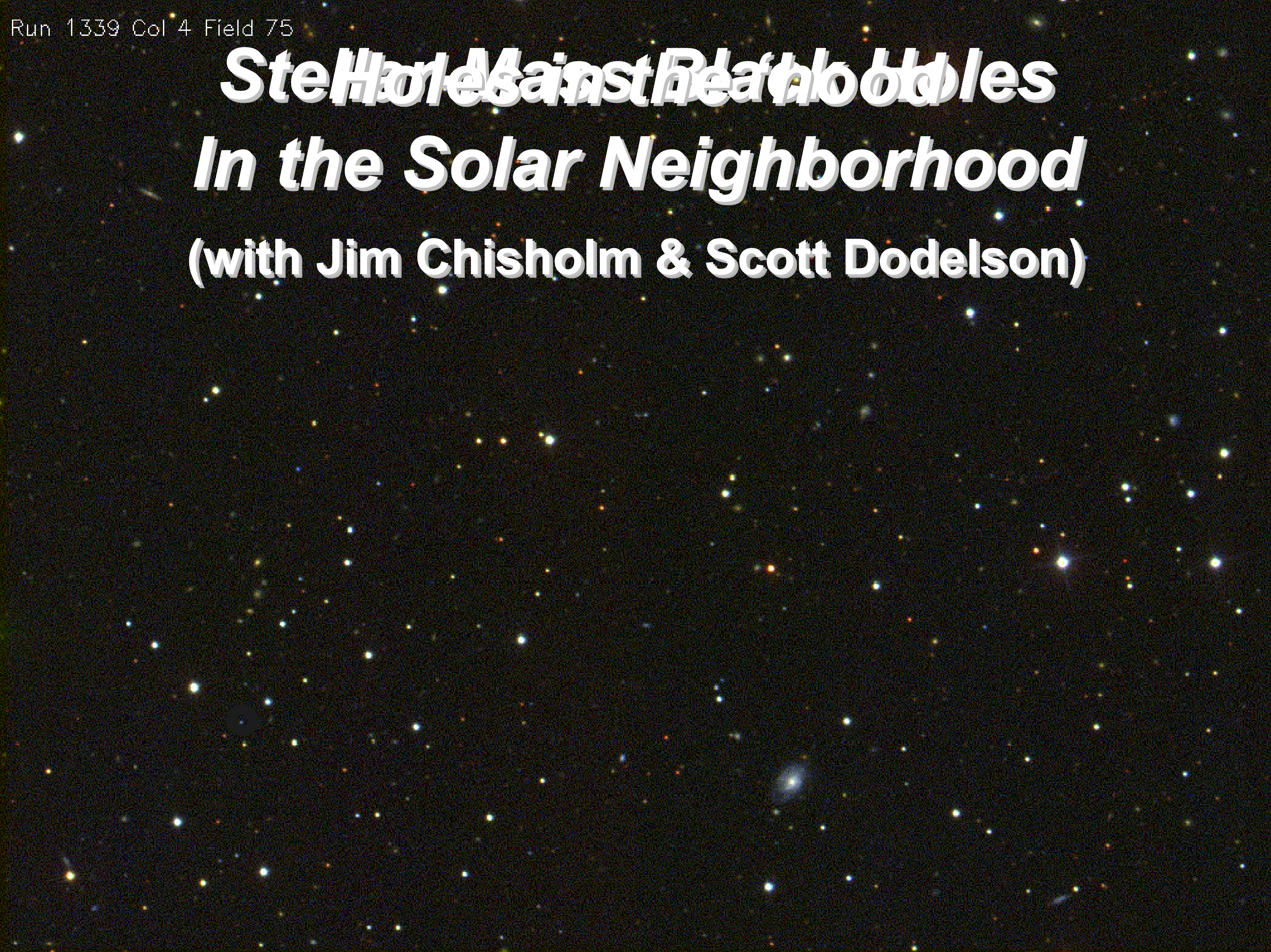
Event 2
A_blue
A_red
A_red/A_blue
0
1
2
3
0.5
1.5
540
560
580
600
days from 2 Jan 1992

Microlensing black-hole candidates





Bennett et al.
(also Mao et al.)



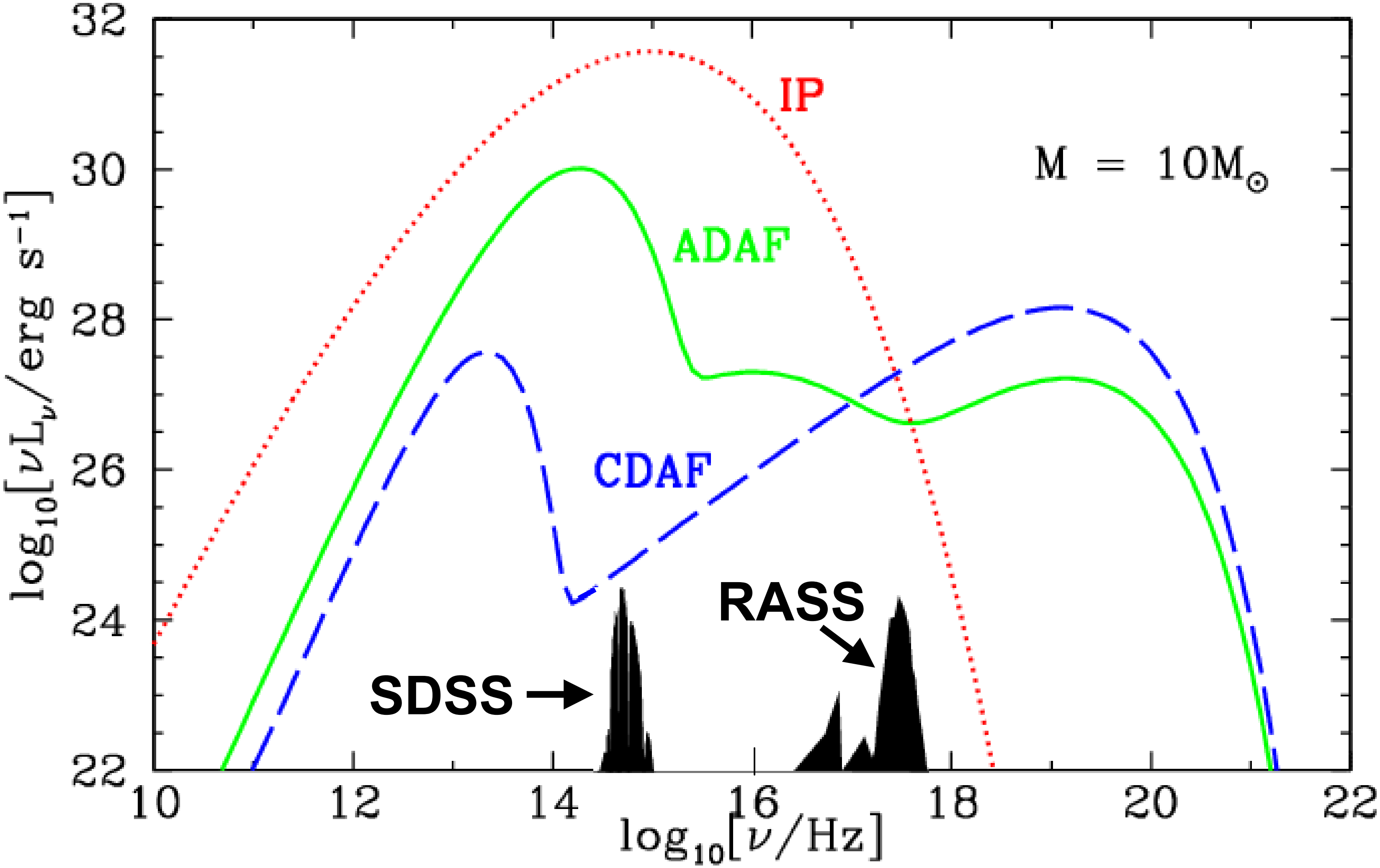
Stellar-Mass Black Holes
Holes in the 'hood
In the Solar Neighborhood

(with Jim Chisholm & Scott Dodelson)

Model spectral energy distributions:

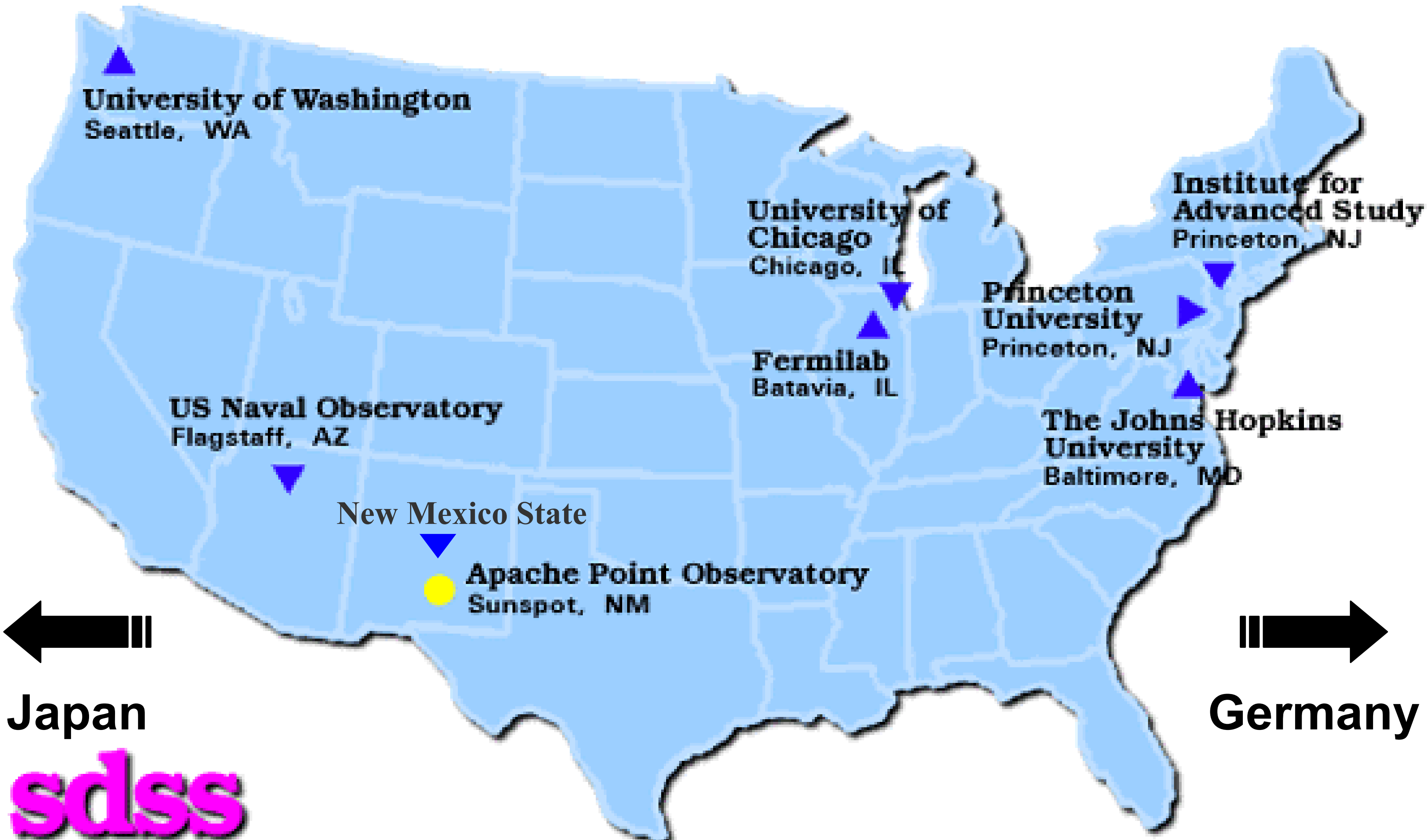
$$L = \int \frac{d\nu}{\nu} \nu L_\nu$$

$\nu L_\nu =$ spectral energy distribution (contribution per decade)



Sloan: a 2.5m telescope & instruments to

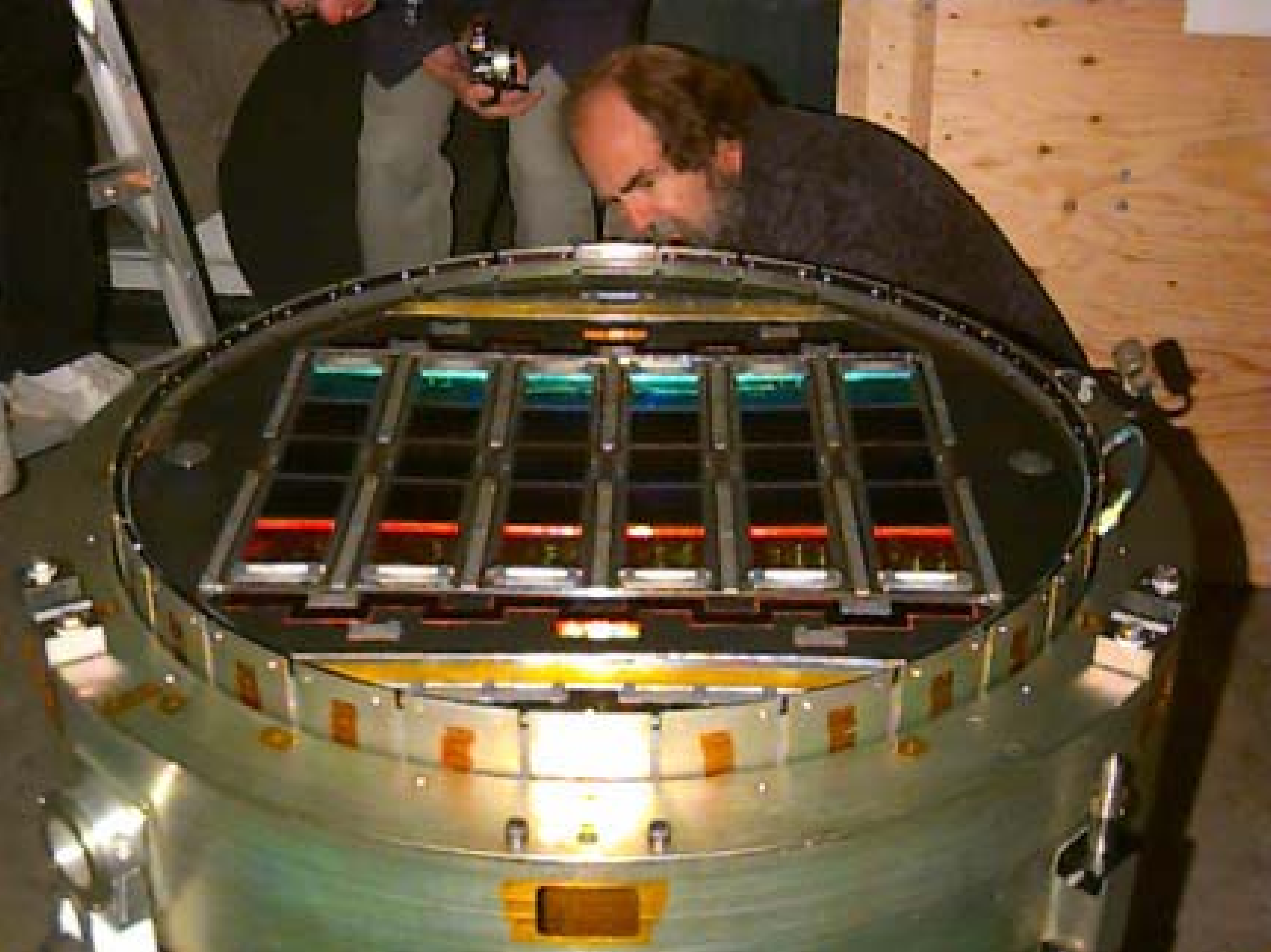
1. image the sky to 23rd mag in 5 colors (10^9 objects)
2. take the spectra of 10^6 objects (mostly extragalactic)



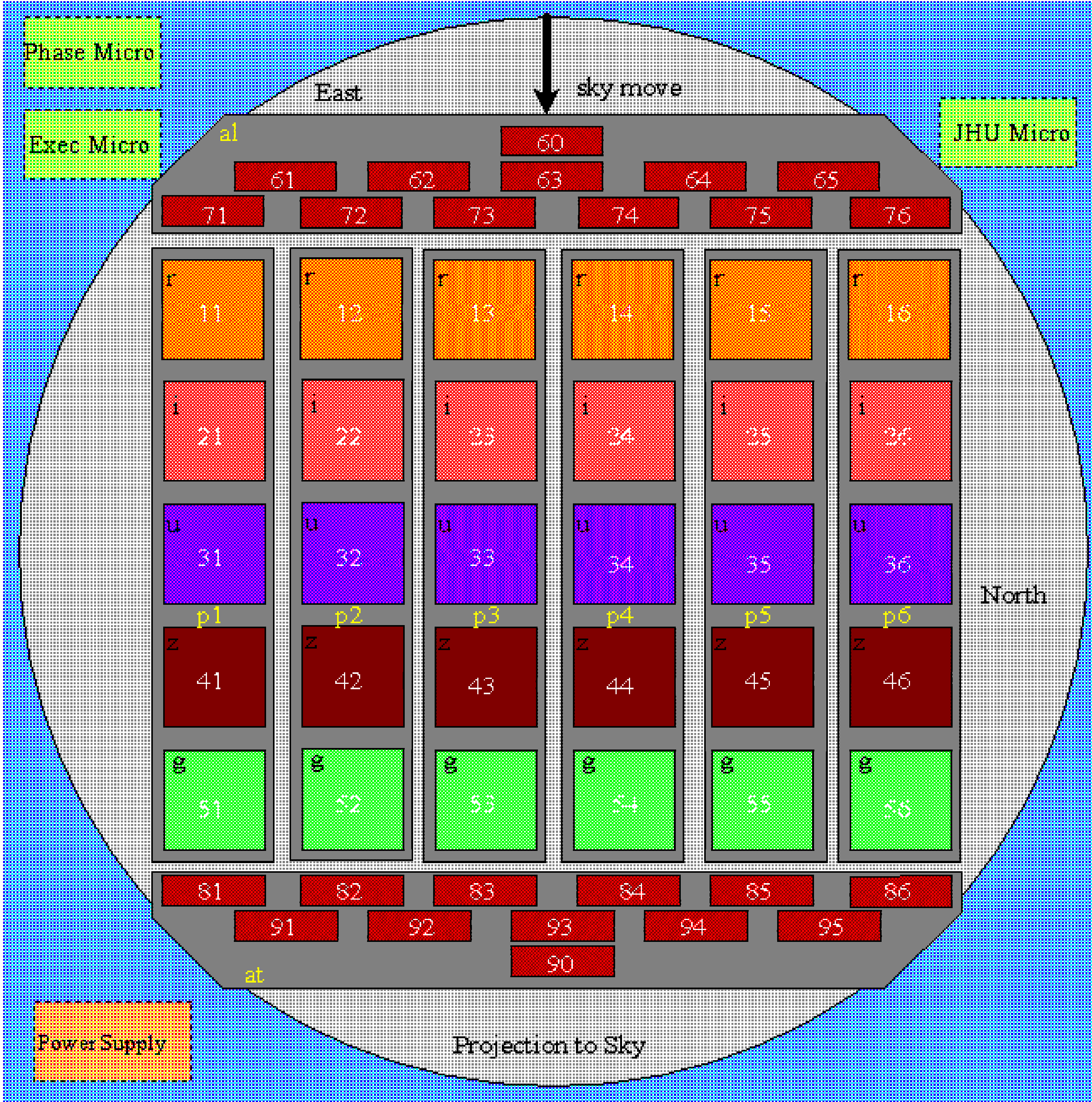
SDSS

2.5 m telescope

data acquisition system

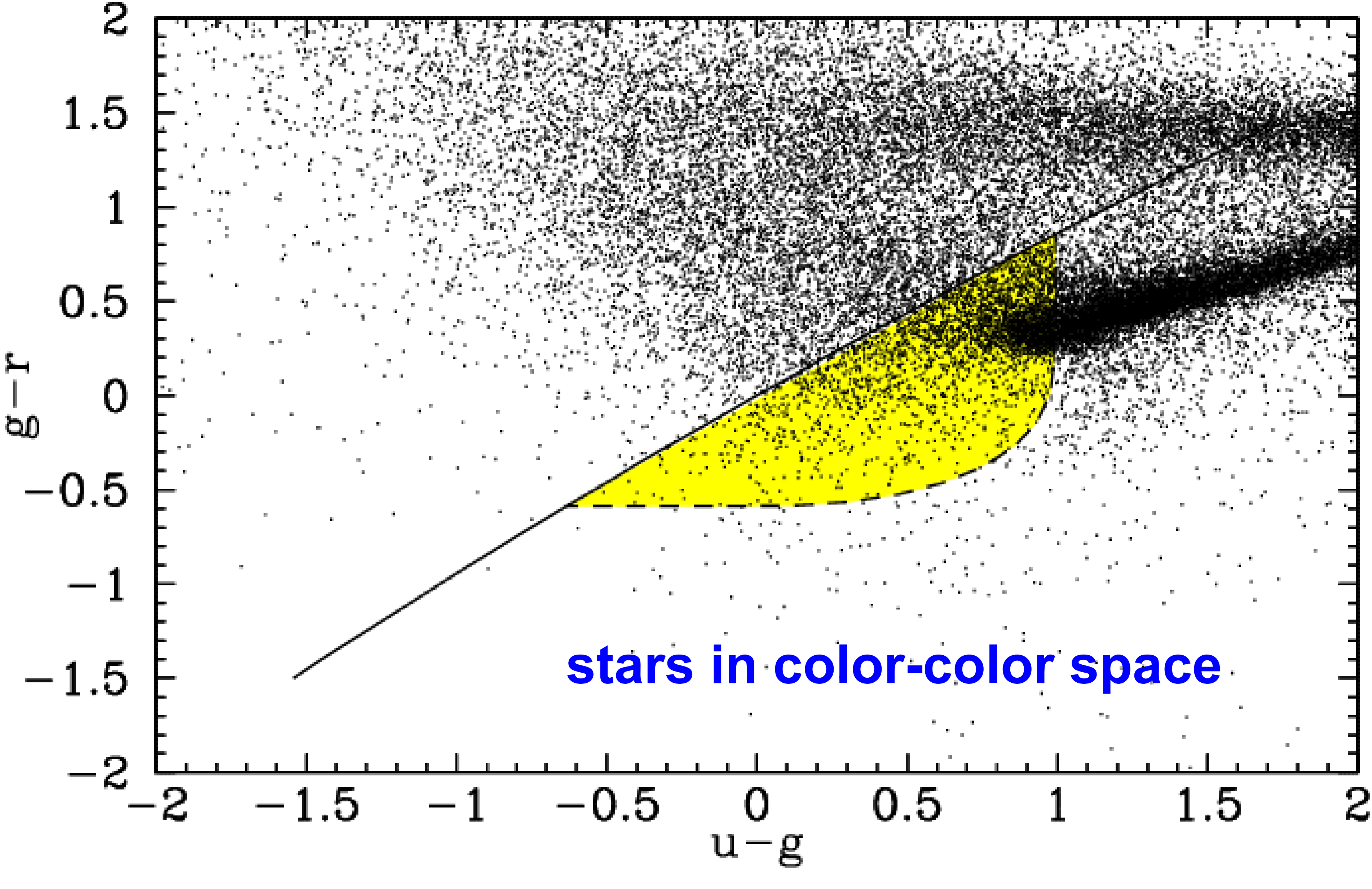


SDSS camera



Phase Micro
Exec Micro
East
sky move
JHU Micro
a1
60
61
62
63
64
65
71
72
73
74
75
76
r 11
r 12
r 13
r 14
r 15
r 16
i 21
i 22
i 23
i 24
i 25
i 26
u 31
u 32
u 33
u 34
u 35
u 36
p1
p2
p3
p4
p5
p6
North
z 41
z 42
z 43
z 44
z 45
z 46
g 51
g 52
g 53
g 54
g 55
g 56
81
82
83
84
85
86
91
92
93
94
95
90
at
Power Supply
Projection to Sky

Color-color space

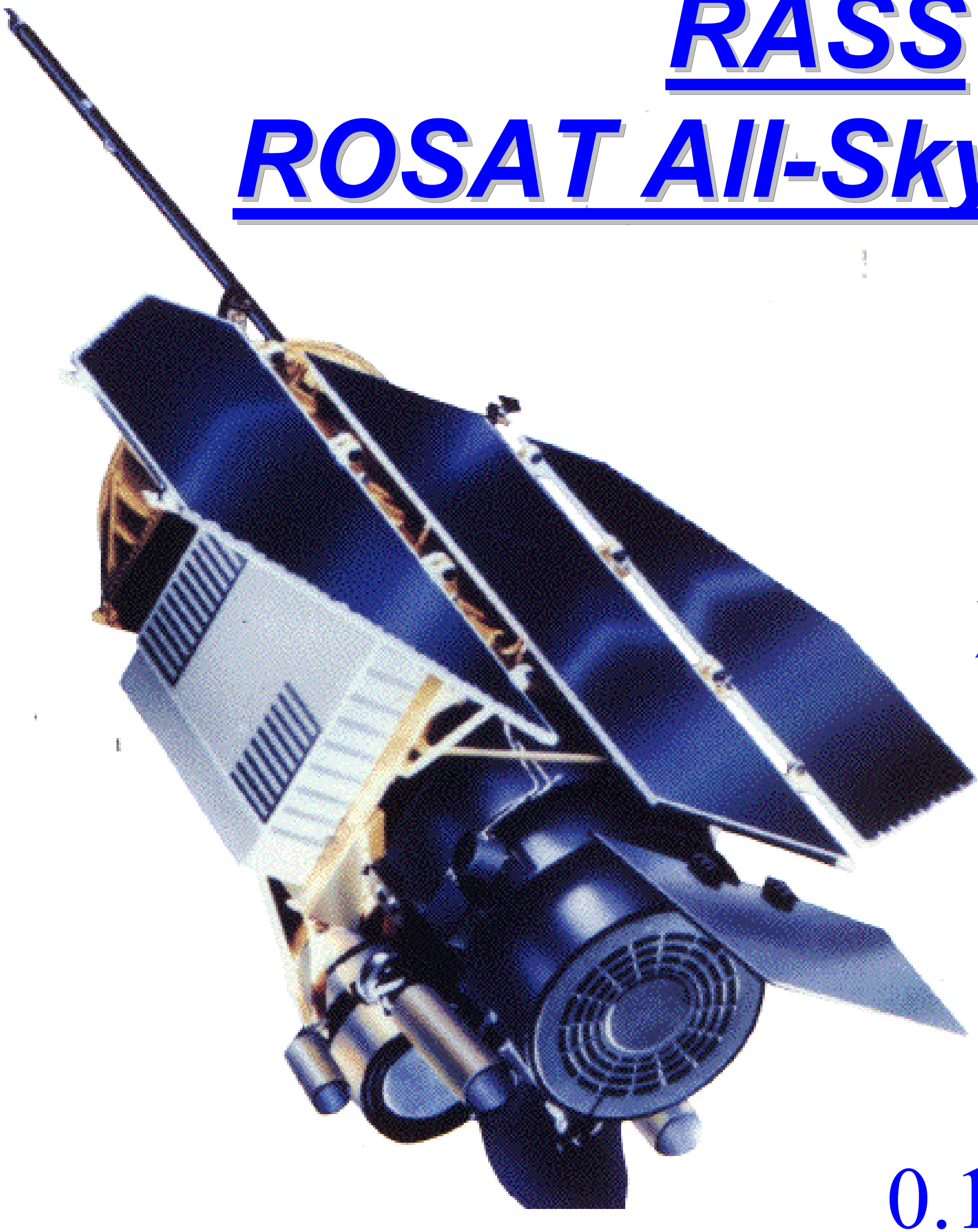


Color-color cut + RASS detection

SDSS Early Data Release = 3.7 million objects

SDSS color cut = 150,000

RASS
ROSAT All-Sky Survey



ROSAT

Röntgen Satellite

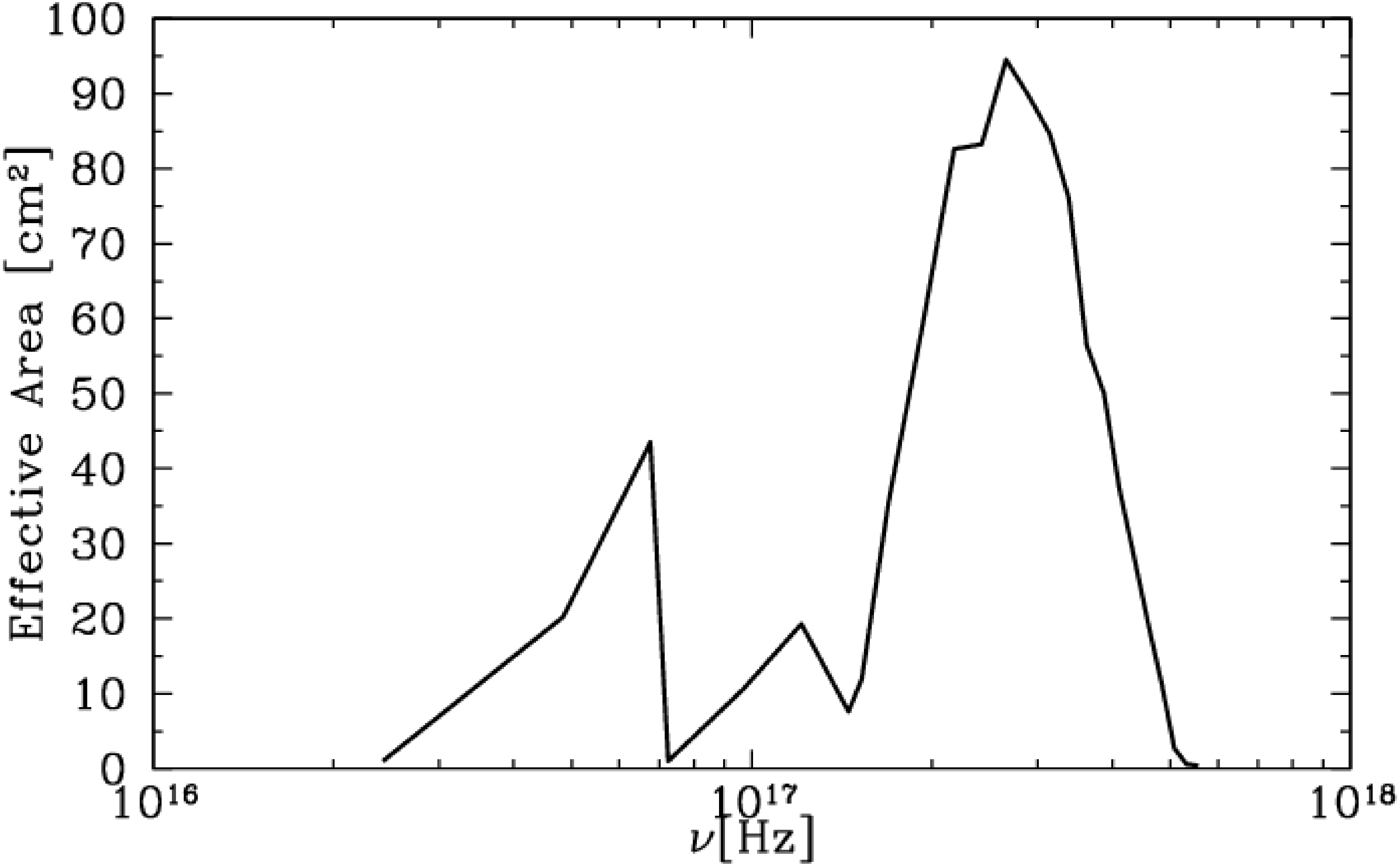
X-Ray Observatory

Germany/US/UK

1990-1999

$0.1\ \text{keV} \leq E \leq 2.4\ \text{keV}$

ROSAT effective area



Color-color cut + RASS detection

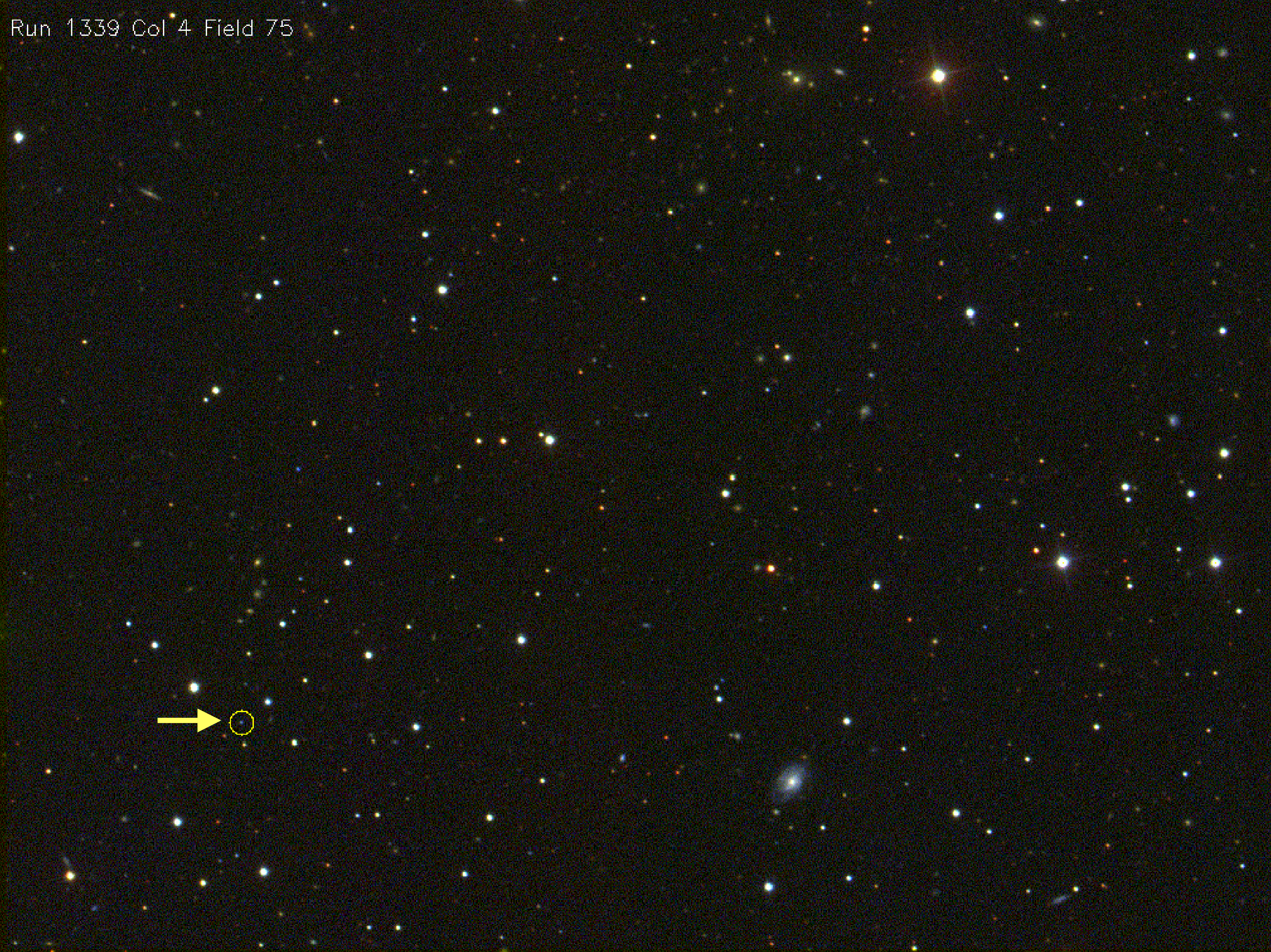
SDSS Early Data Release = 3.7 million objects

SDSS color cut = 150,000

SDSS + RASS = 47

47 is a manageable number
(can examine each individually)
7 targeted for spectroscopy by SDSS
(5 stars + 2 QSOs)
Can define measure of how far from stellar locus in
4 color-color spaces


Run 1339 Col 4 Field 75


Run 1339 Col 4 Field 75

Most of the universe is dark!

- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars

  brown red white
- Black holes
- The weight of space

gravitational microlensing

Most of the universe is dark !

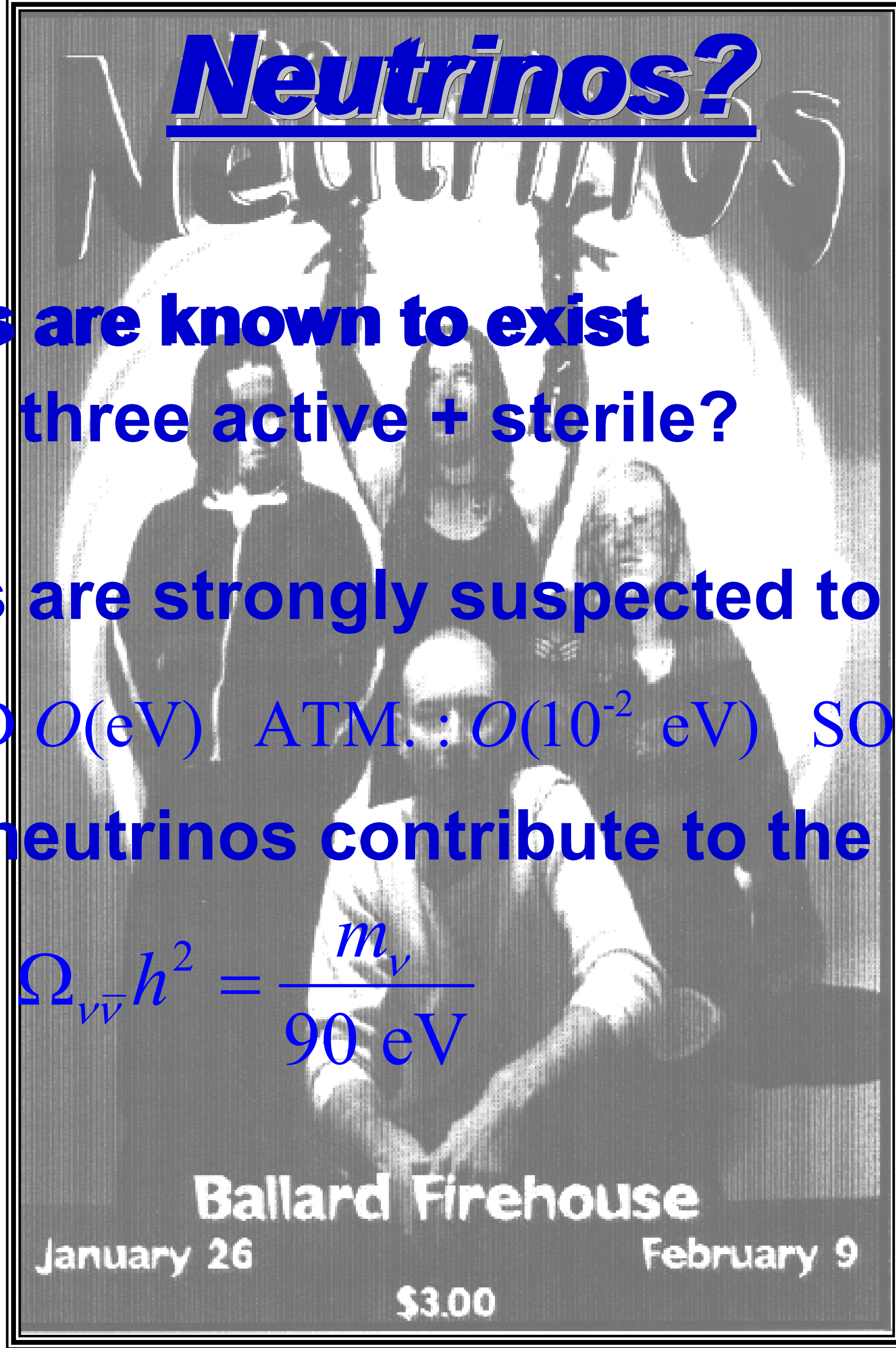
- Modified Newtonian dynamics
- Planets
- Mass disadvantaged stars

  brown red white

- Black holes

gravitational microlensing

- The weight of space
- Fossil remnant of the big bang



Neutrinos?

- **Neutrinos are known to exist**

  three active + sterile?

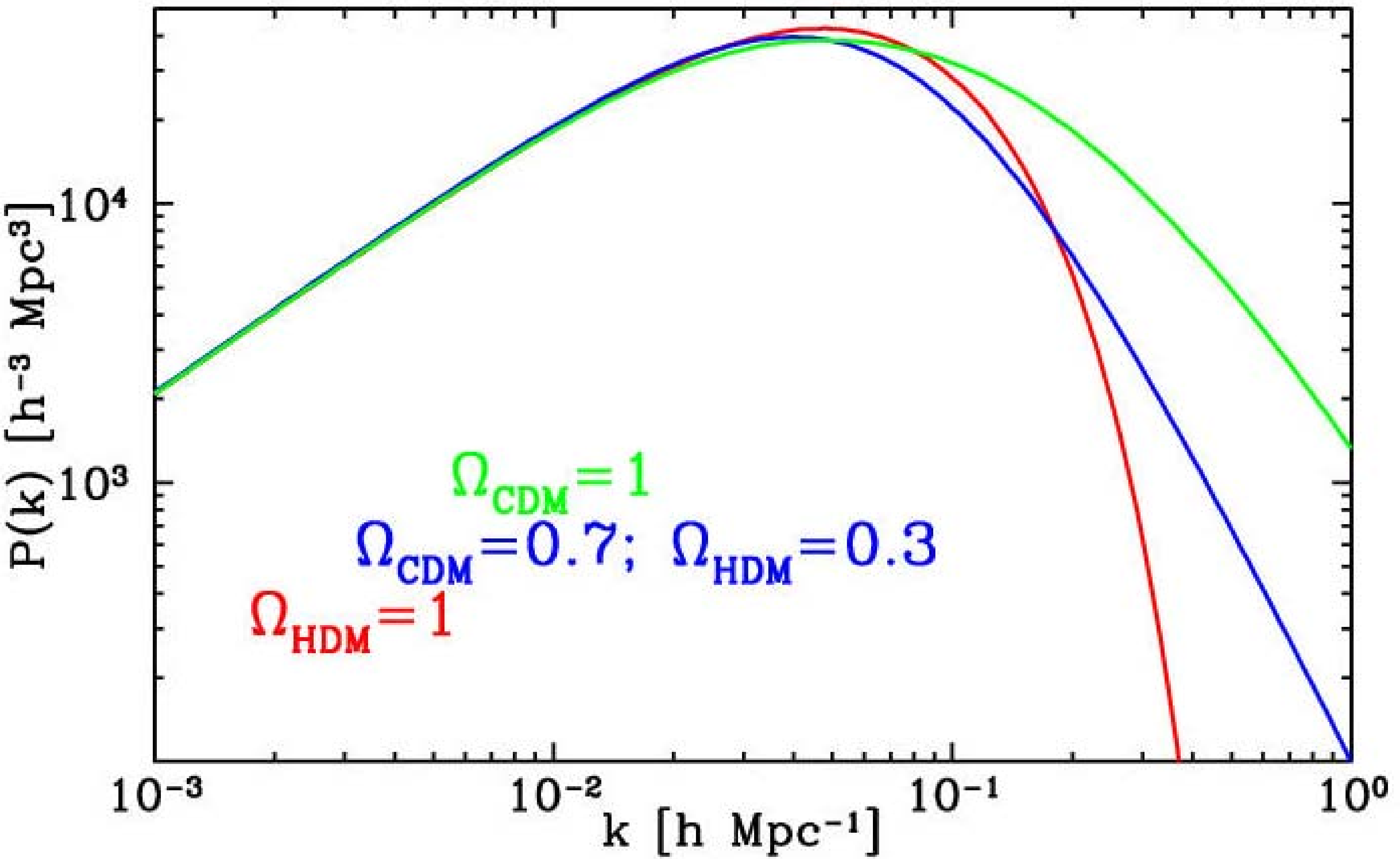
- **Neutrinos are strongly suspected to have mass**

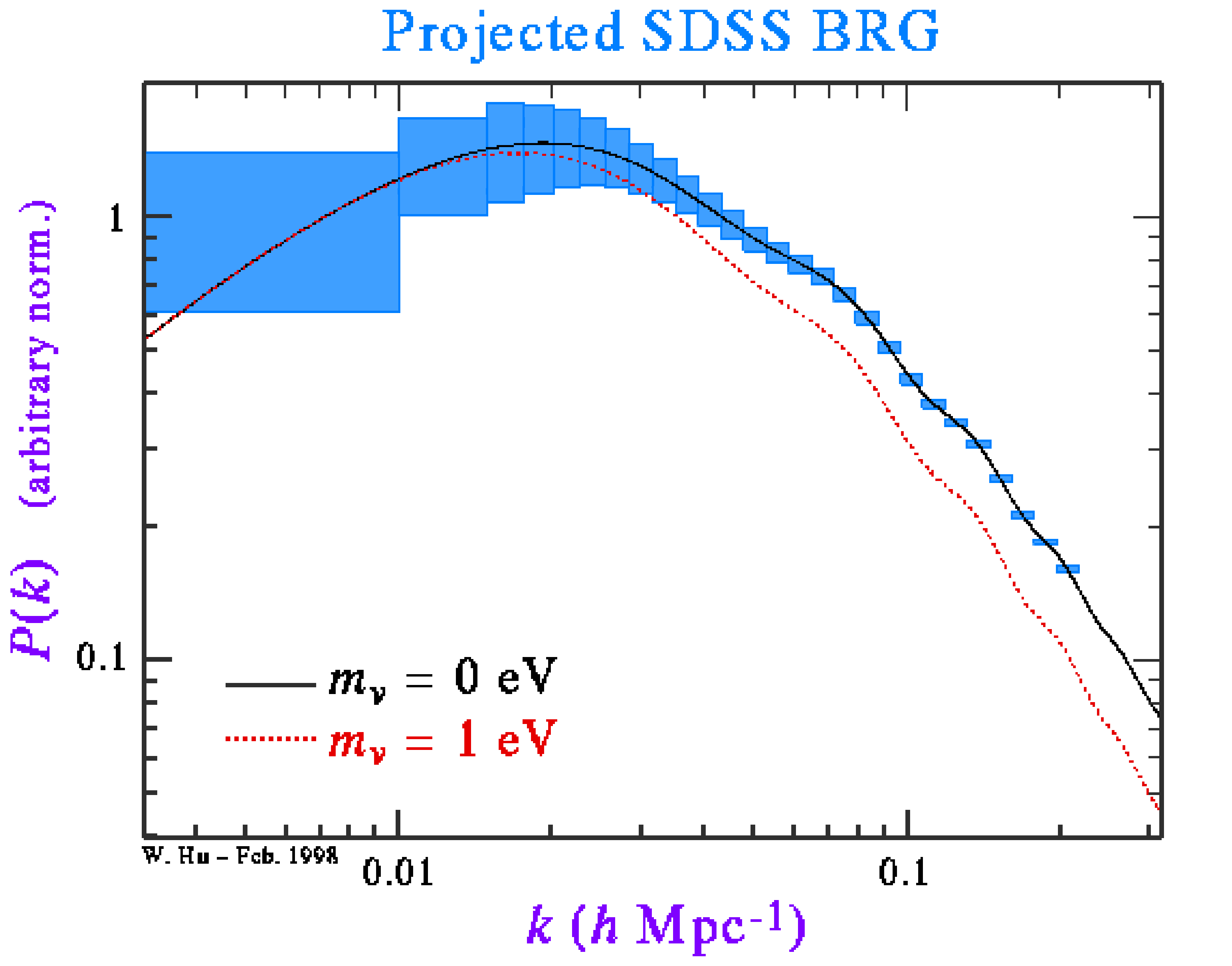
  LSND O(eV) ATM. : $O(10^{-2}$ eV) SOLAR: $O(10^{-3}$ eV)

- **Massive neutrinos contribute to the mass density**

$$\Omega_{\nu\bar{\nu}} h^2 = \frac{m_\nu}{90\ \mathrm{eV}}$$

The evolved spectrum





Projected SDSS BRG
P(k) (arbitrary norm.)
1
0.1
0.01
0.1
k (h Mpc-1)
$m_\nu = 0$ eV
$m_\nu = 1$ eV
W. Hu – Feb. 1998

NEUTRINO MASS AND MIXING IMPLIED BY UNDERGROUND DEFICIT OF LOW ENERGY MUON-NEUTRINO EVENTS

John G. LEARNED, Sandip PAKVASA, and Thomas J. WEILER [1]
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA

Received 14 March 1988

Recent observations of a deficit of cosmic ray muon-neutrino interactions in underground detectors suggest that the muon neutrinos may have oscillated to another state. We examine possible neutrino mass and mixing patterns, and their implications for vacuum and matter effects on solar neutrinos, on neutrinos passing through the earth, and on terrestrial neutrino beams. By invoking the see-saw mechanism of neutrino mass generation, we draw inferences on closure of the universe with neutrino masses, on the number of generations, on t-quark and fourth generation masses, and on the Peccei–Quinn symmetry breaking scale. Testable predictions are suggested.

(d) Relic tau neutrinos have sufficient energy density to close the university

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(8)

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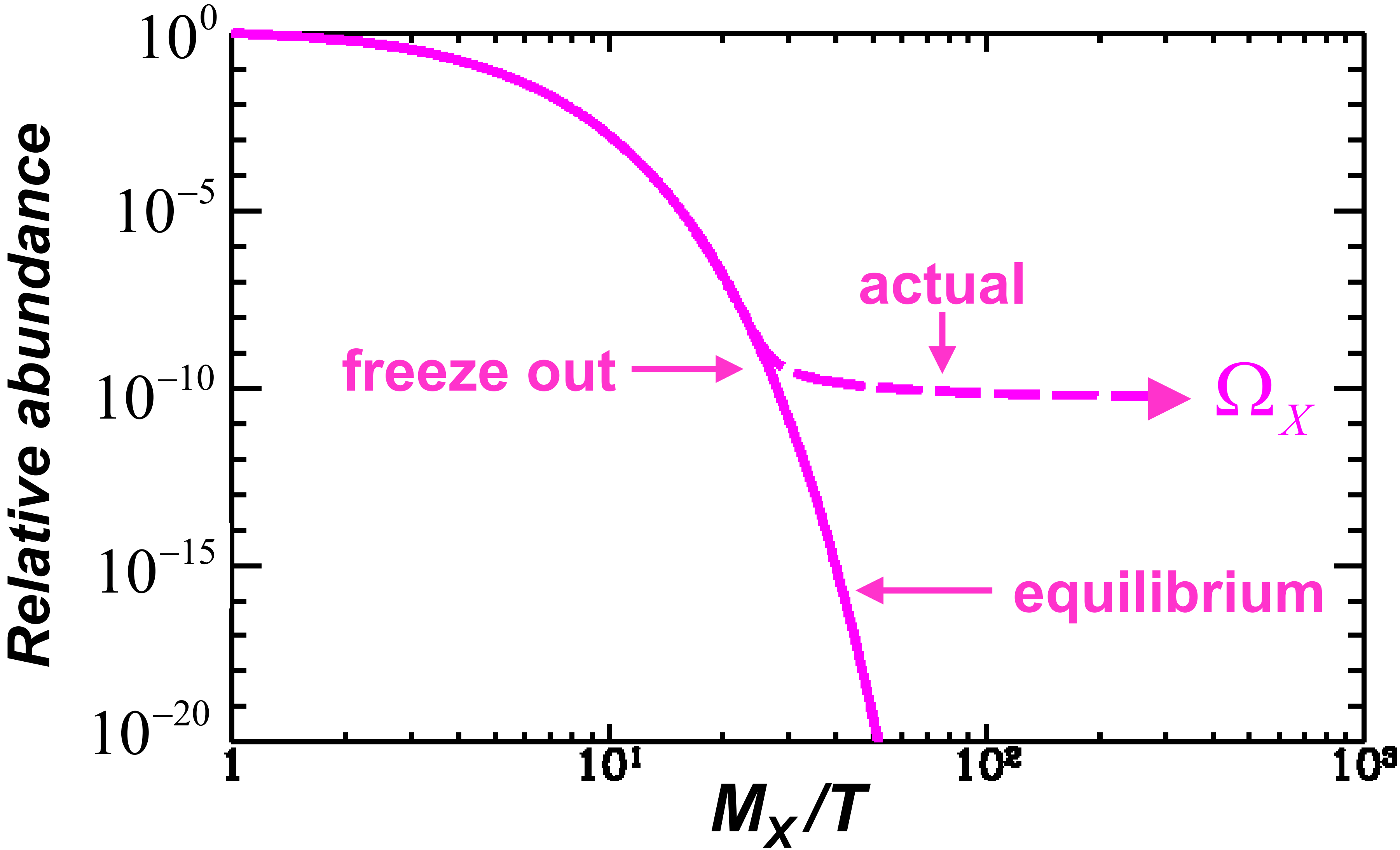
and muon-neutrinos (not antineutrinos) coming through the earth at $E_\nu \sim 50 - 150$ GeV have matter-enhanced oscillations and the muon-neutrinos down/up flux ratio should be even larger than the nonmatter-enhanced expectation (for energies ~ 1 TeV and larger oscillations are suppressed in the earth). Detectors capable of distinguishing μ^- from μ^+ have increased sensitivity to matter effects [10]. (c) A 40% $\nu_\mu \leftrightarrow \nu_e$ conversion should be observable in a detector at a distance L from the neutrino source for the integrated flux satisfying $E/\mathrm{GeV} \lesssim 0.04\, L/\mathrm{km}$. (d) Relic tau neutrinos have sufficient energy density to close the university [11] (thus favoring hot dark matter over cold): the tau-neutrino mass may be determined from the time spread of events from a galactic supernova. (e) There are only three generations: the mass of a fourth-generation heavy lepton is bounded from below by the UA1 data [12] and from

Cold thermal relics

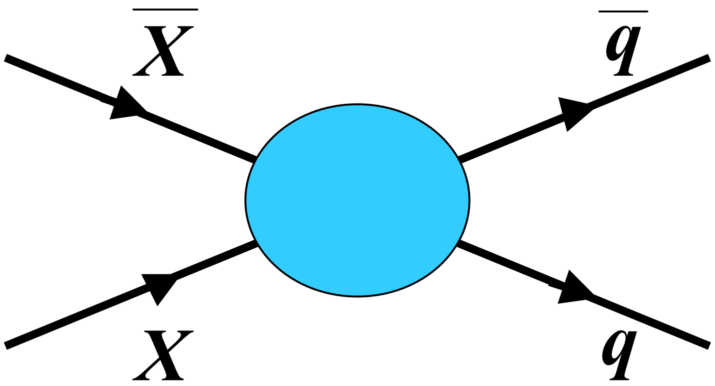


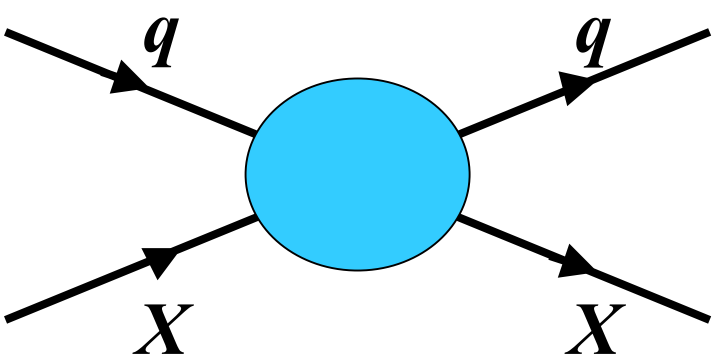
$\Omega_X \propto \sigma_A^{-1}$ *(independent of mass)*

Cold thermal relics

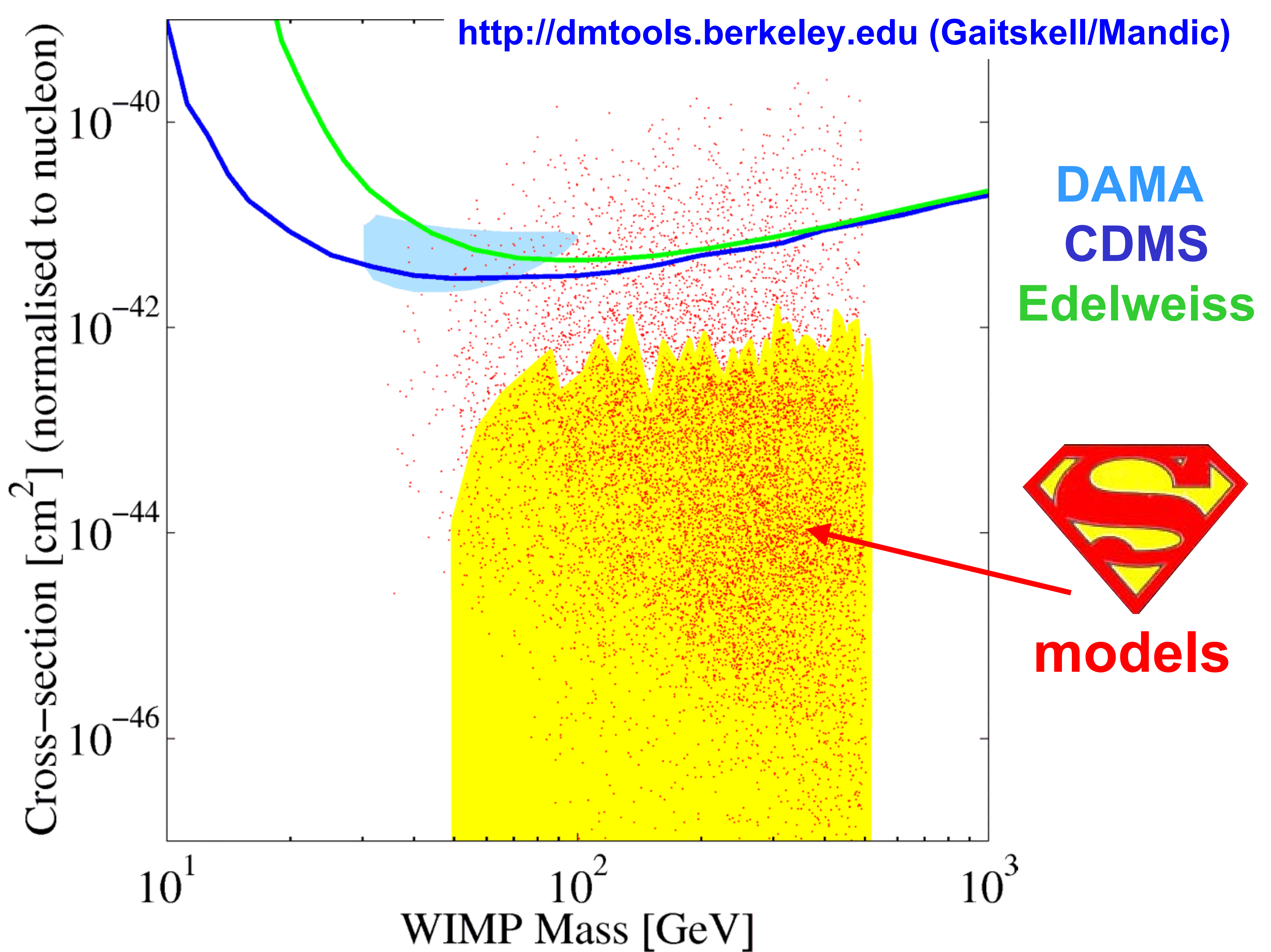
$$\Omega_X h^2 \sim \langle \sigma_A v \rangle^{-1}$$

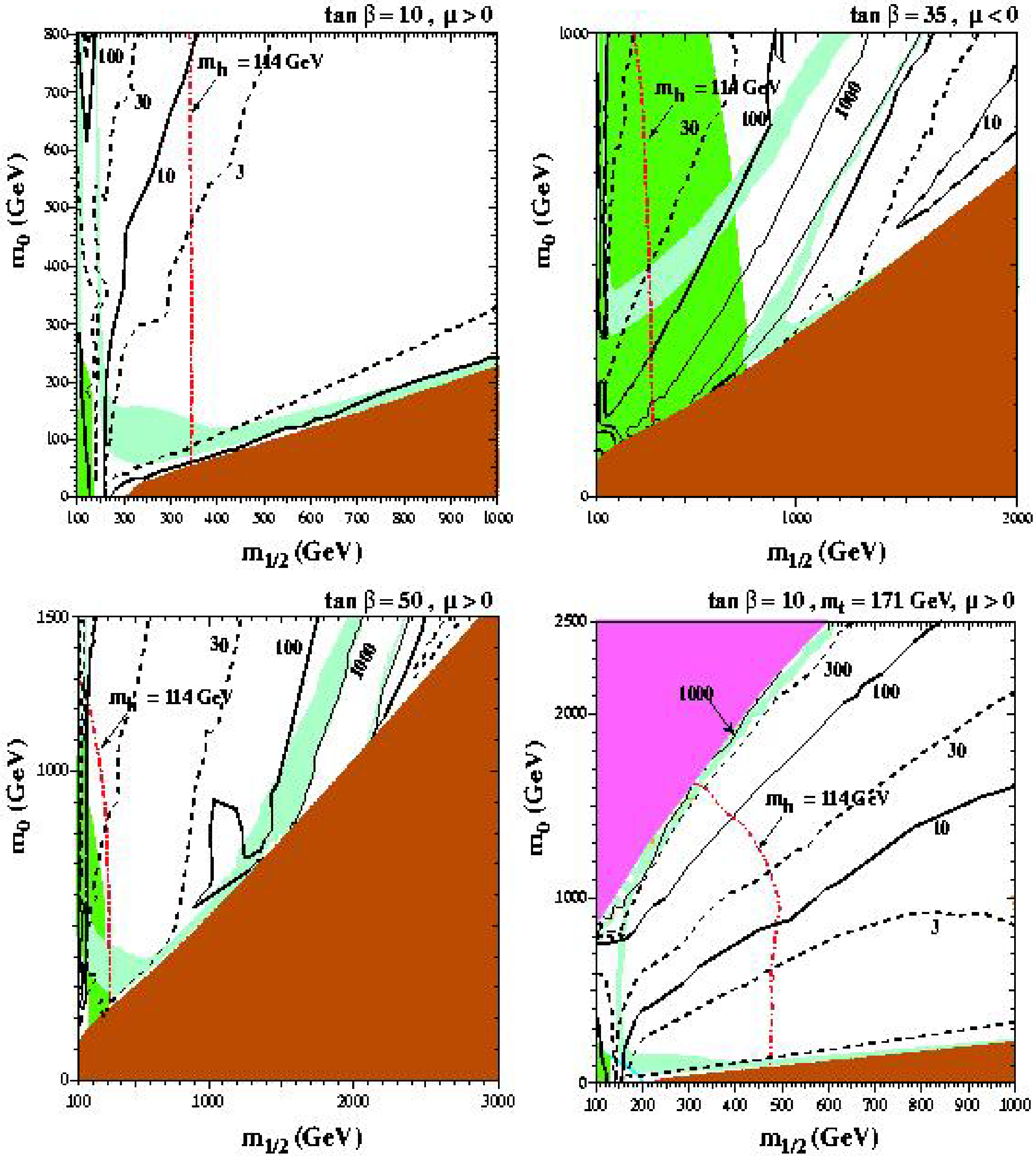
$$\sigma_A \Leftrightarrow \Omega_X \qquad\qquad \sigma_A \Leftrightarrow \sigma_S$$





Goodman & Witten


http://dmtools.berkeley.edu (Gaitskell/Mandic)
DAMA
CDMS
Edelweiss
models
Cross−section [cm^2] (normalised to nucleon)
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^1
10^2
10^3
WIMP Mass [GeV]



CMSSM

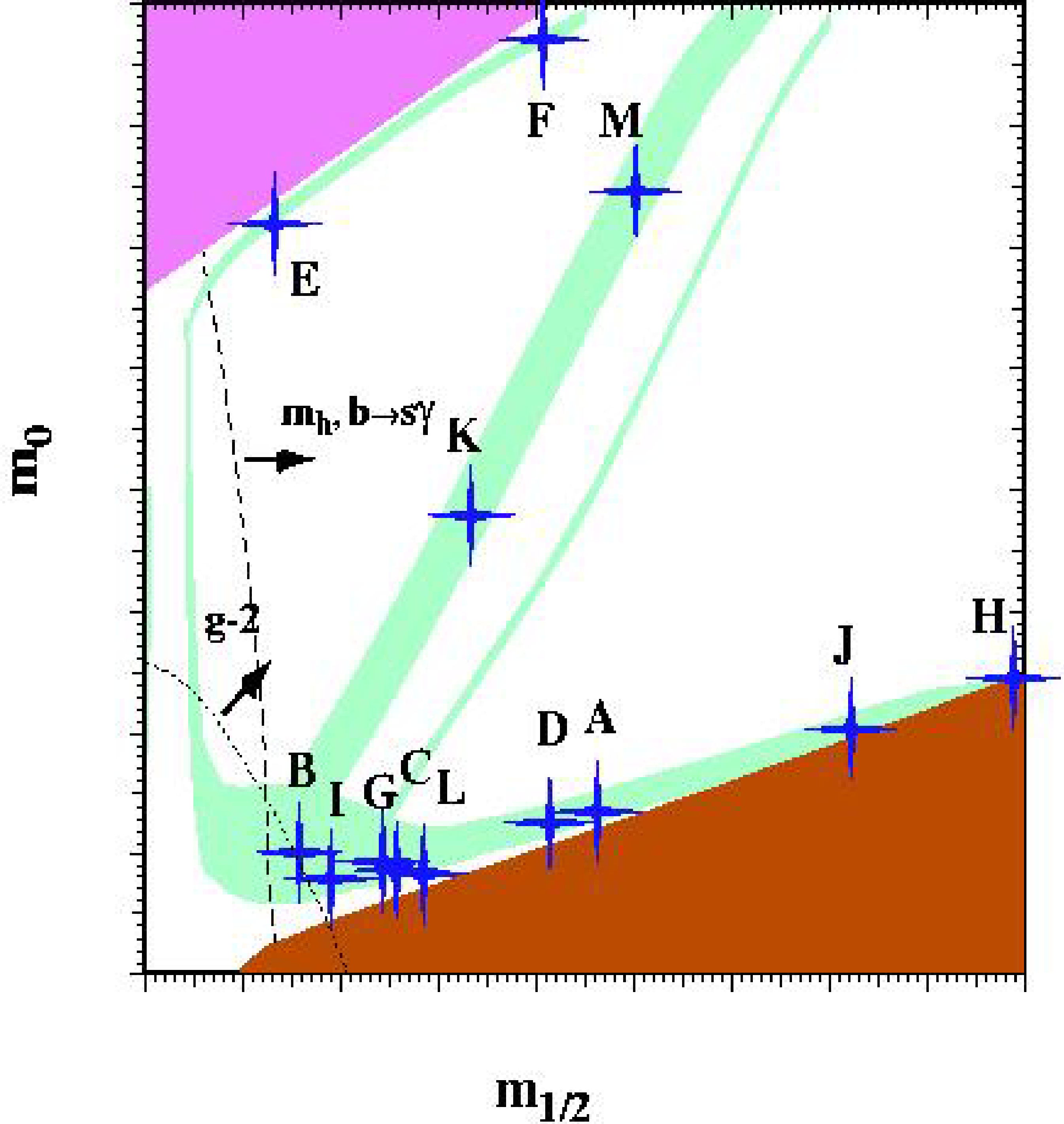
$m_0 =$ universal scalar mass

$m_{1/2} =$ gaugino mass

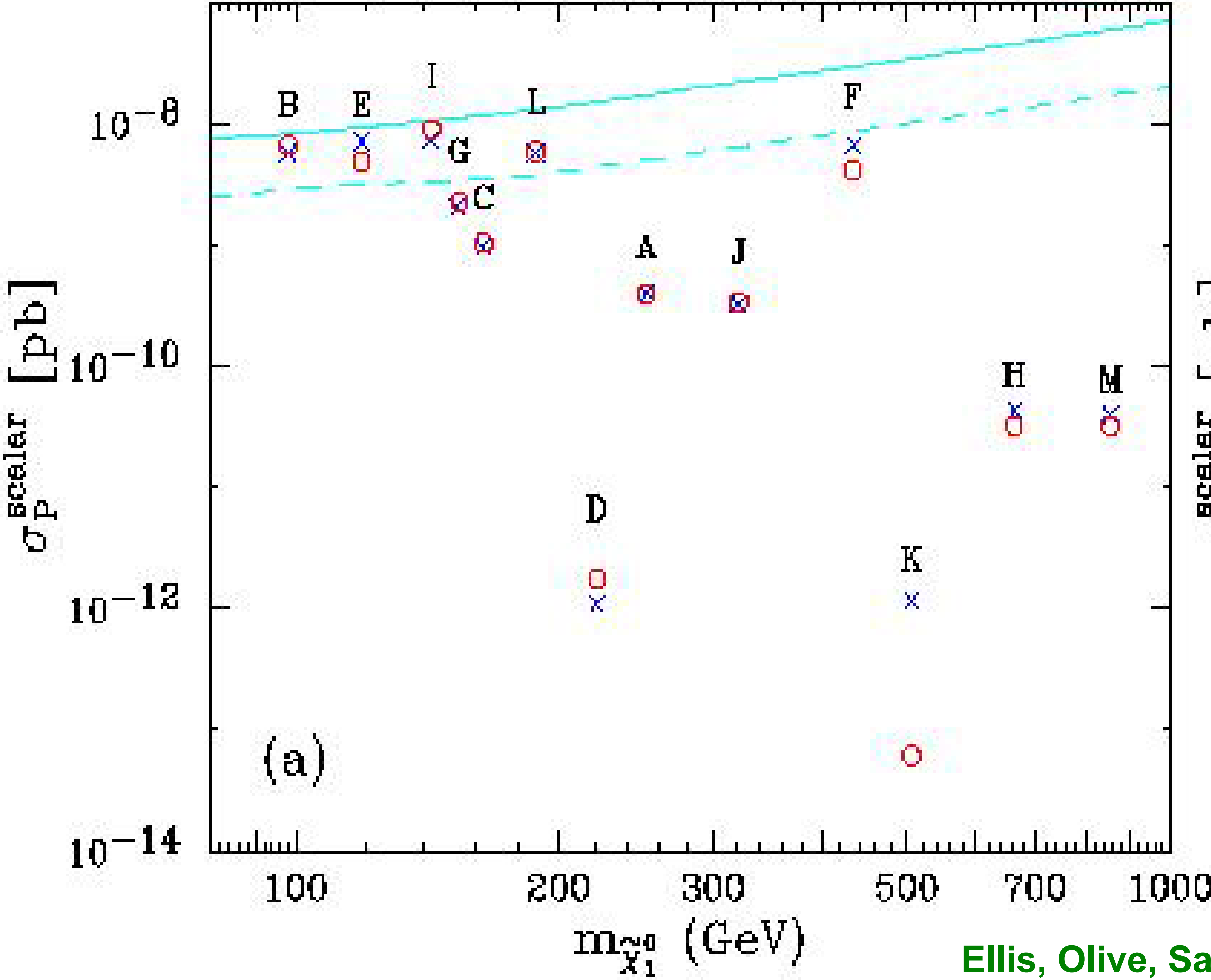
$\tan\beta =$ ratio of vevs

$|\mu|$ determined

Ellis, Olive, Santoso



Ellis, Olive, Santoso



Ellis, Olive, Santoso

Thermal WIMP: interaction & mass limit

Ω_X depends on the anihilation strength ($\Omega_X \propto \sigma_A^{-1}$)

$\Omega_{\rm X} \approx 1$ annihilation strength $\approx$ electroweak scale

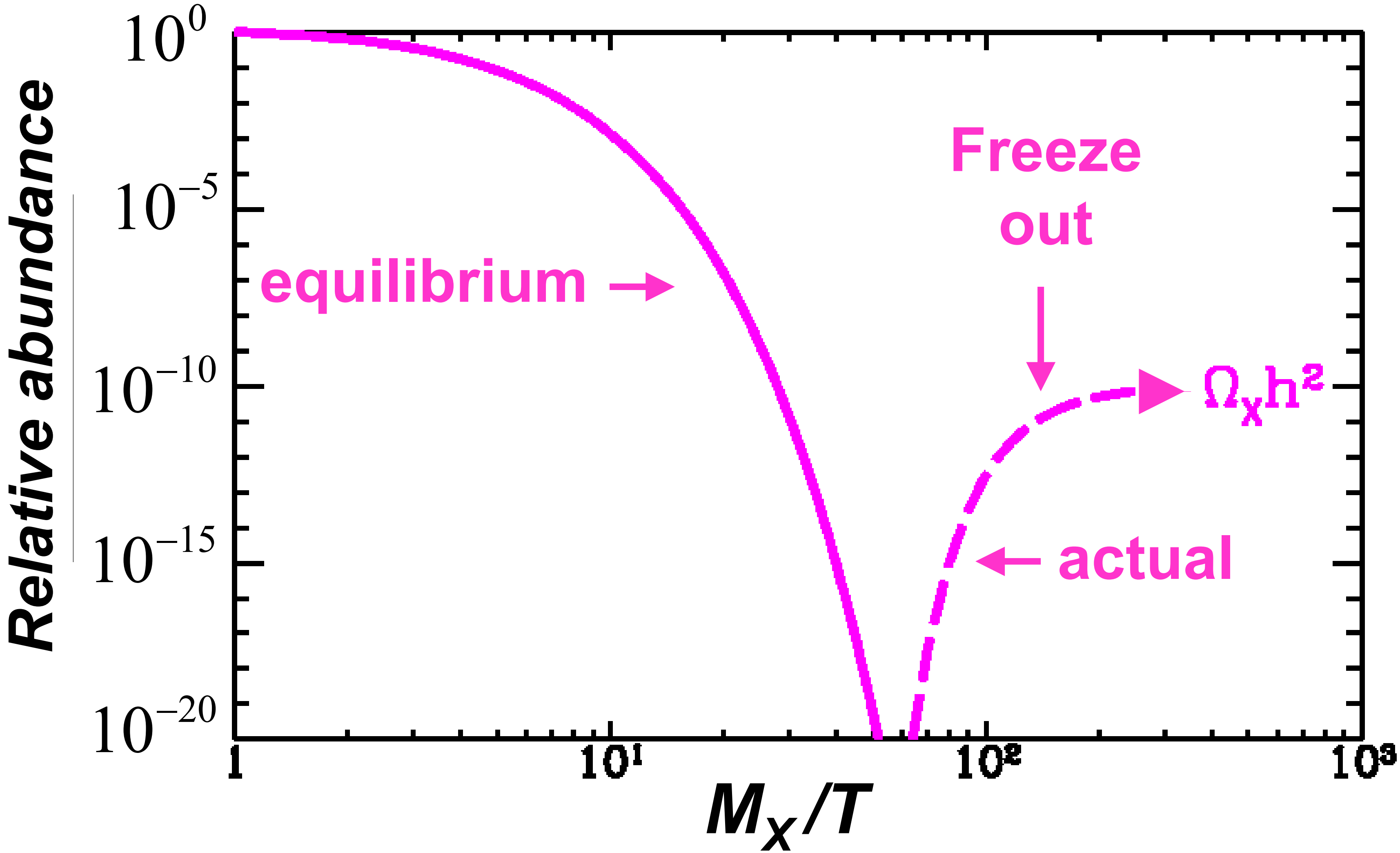
annihilation strength $\rightarrow$ interaction strength

$\sigma_A \leq \dfrac{8\pi}{m_X^2}$ unitarity limit to the cross section

$$\Omega_X \leq 1 \Rightarrow M_X \leq 200\ \mathrm{TeV}$$

Thermal WIMP: Interaction strength determined
Mass undetermined (but < 200 TeV)

Nonthermal relics



$Y >> Y_{EQ}$ at freezeout

Expanding universe → particle creation

(Arnowit, Birrell, Bunch, Davies, Deser, Ford, Fulling, Grib, Hu, Kofman, Mostepanenko, Page, Parker, Starobinski, Unruh, Vilenkin, Wald, Zel'dovich,…)

first application:

- **density perturbations from inflation**
- **gravitational waves from inflation**

(Guth & Pi; Starobinski; Bardeen, Steinhardt, & Turner; Hawking; Rubakov; Fabbi & Pollack; Allen)

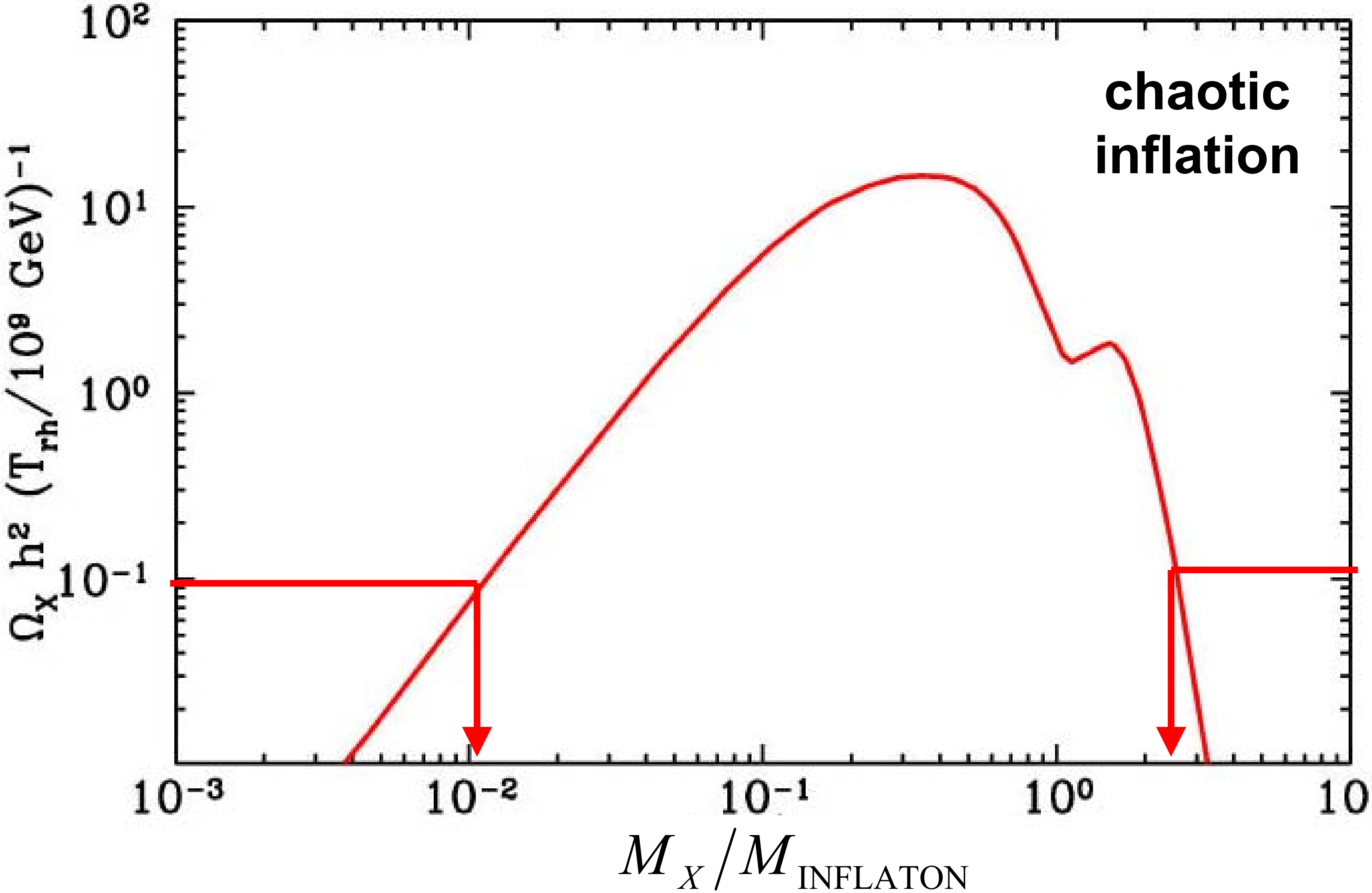
new application: **dark matter**

(Chung, Kolb, & Riotto; Kuzmin & Tkachev)

- **require (super)massive particle "X"**
- **stable (or at least long lived)**
- **initial inflationary era followed by radiation/matter**

WIMPZILLA production

Chung, Kolb, Riotto (also Kuzmin & Tkachev)



$$\Omega_X \approx 1 \quad \text{for} \quad M_X / M_{\text{INFLATON}} \approx 1 \Rightarrow M_X \approx 10^{10} \text{ to } 10^{15} \text{GeV}$$

Superheavy particles

Inflaton mass (in principle measurable from gravitational wave background, guess $10^{12}\ \mathrm{GeV}$) may signal a new mass scale in nature.

Other particles may exist with mass comparable to the inflaton mass.

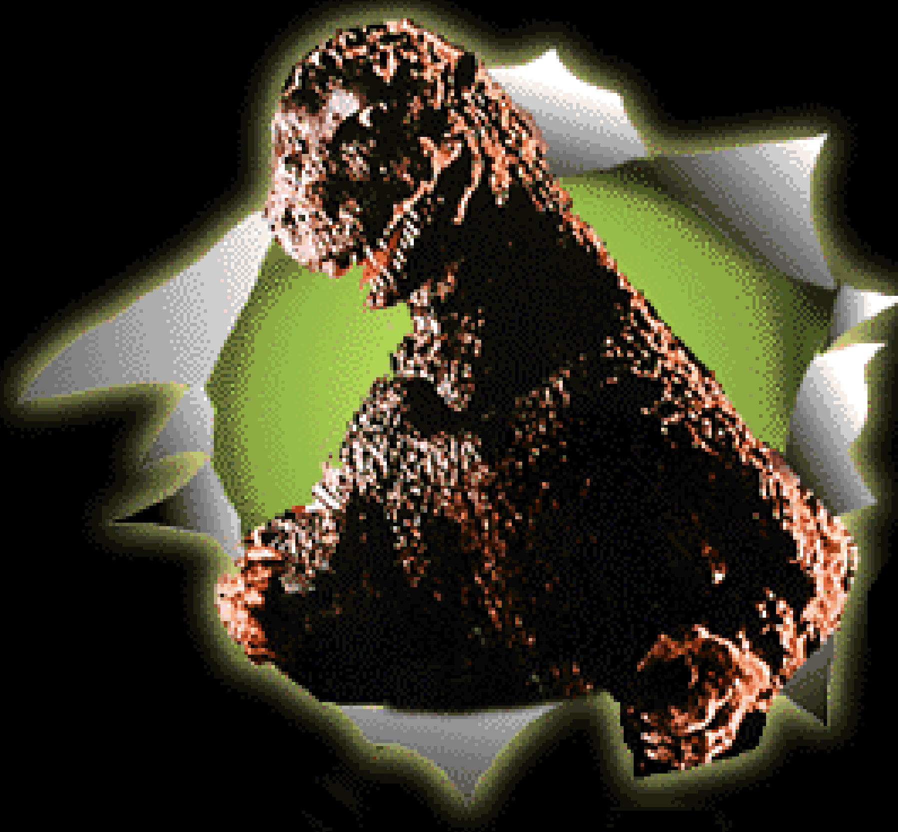
Superheavy relic (wimpzilla) characteristics:

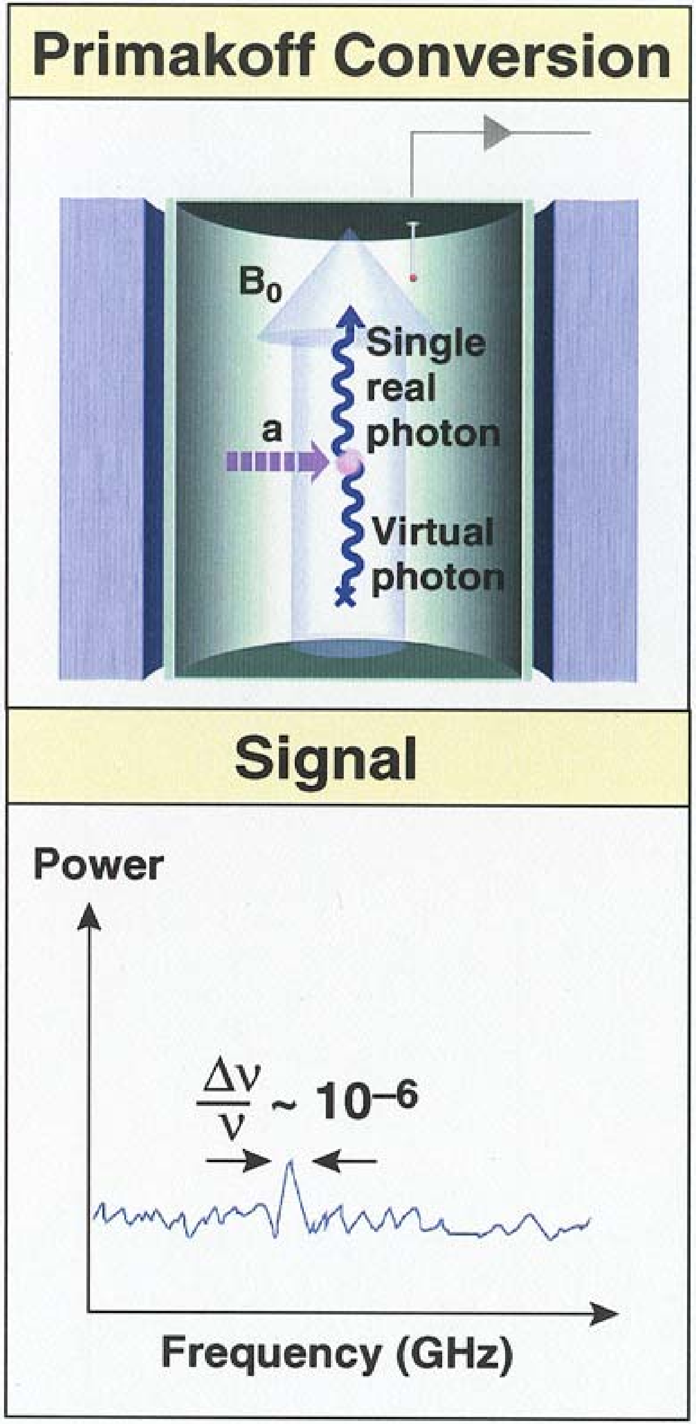
- **Supermassive:** ***10^9 - 10^{19}*** **GeV (~** ***10^{12}*** **GeV ?)**
- **abundance may depend only on mass**
- **abundance may be independent of interactions**
  - **sterile?**
  - **electrically charged?**
  - **strong interactions?**
  - **weak interactions?**
- **unstable (lifetime > age of the universe)?**

Decay:	Ultra High Energy Cosmic Rays
Annihilate:	Galactic Center, Sun
Isocurvature Perturbations:	Structure Formation, CMB
Direct Detection:	Bulk, Underground Searches

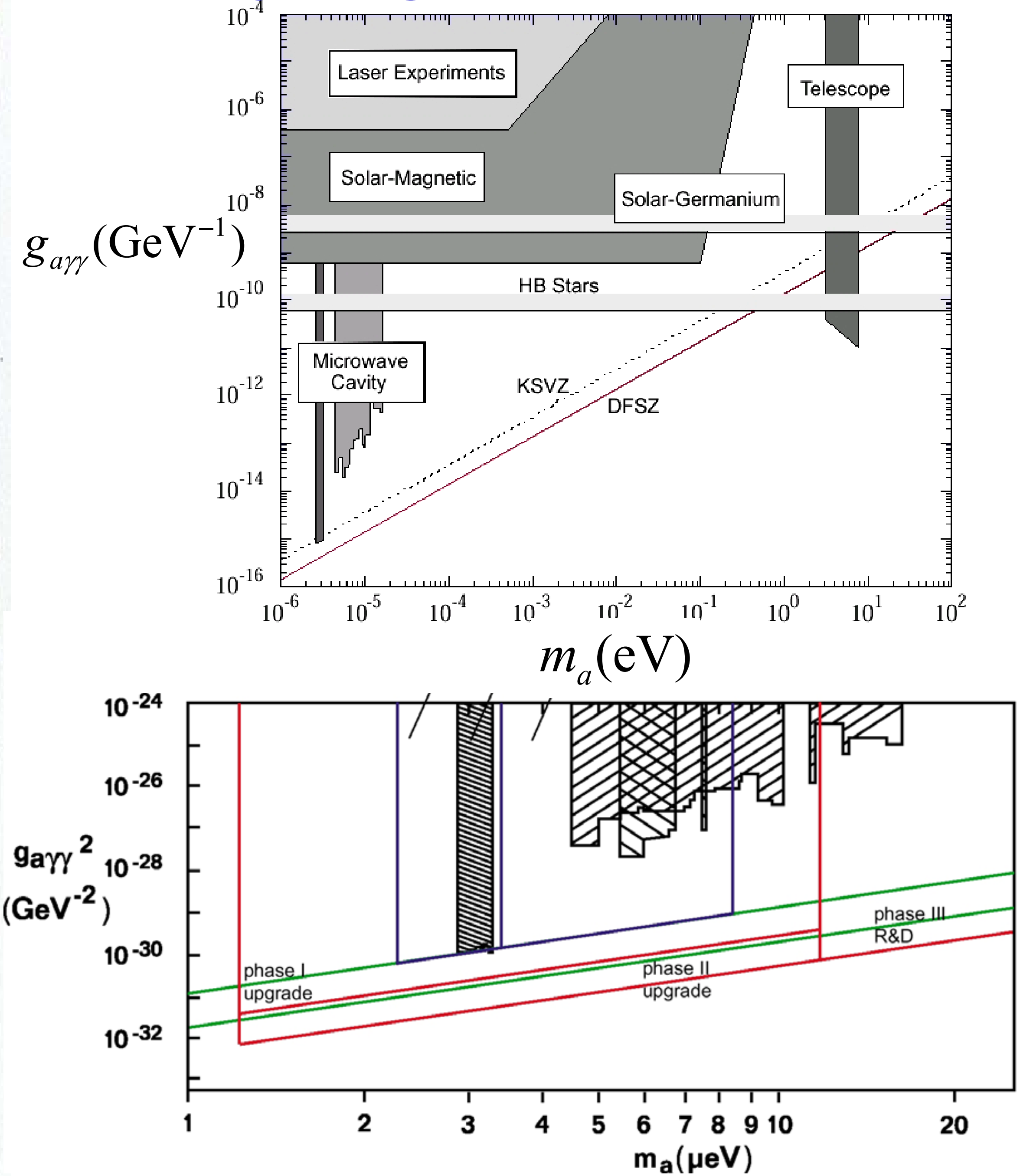
Dark Matter

WIMP or **WIMPZILLA**





www-phys.llnl.gov/N_Div/Axion/axion.html



Particle Dark Matter Candidates

- neutrinos (hot dark matter)
- sterile neutrinos, gravitinos (warm dark matter)
- LSP (neutralino, sneutrino, …) (cold dark matter)
- axion, axion clusters
- WIMPZILLA
- solitons (B-balls; Q-balls; Odd-balls,….)

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• Origin of structure:

a complex natural phenonenon

• Gravitational instability of perturbations from inflation:

a simple, elegant, compelling explanation

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

- Tommy Gold

What We "Know" *

The matter density is dominated by cold dark matter, ***which we know nothing about!***

The perturbations arise from inflationary dynamics, which depends on particle physics at high energies, ***which we know nothing about!***

The universe is dominated by a cosmological term (dark energy, funny energy, quintessence, polenta, cosmological constant, cosmoillogical constant, ….), ***which we know less than nothing about!***

***It ain't what you don't know, it's what you know that ain't so!**

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